Dark Matter: Overview

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P5 Meeting
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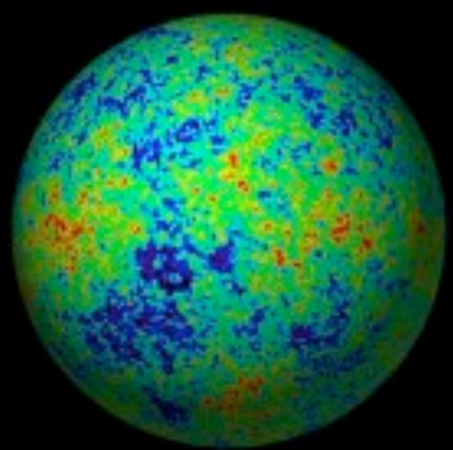
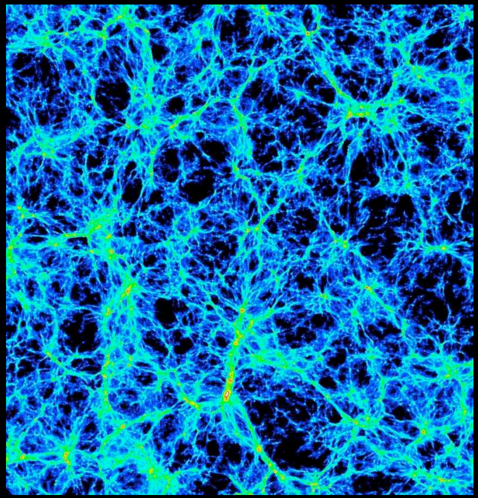
Dark Matter

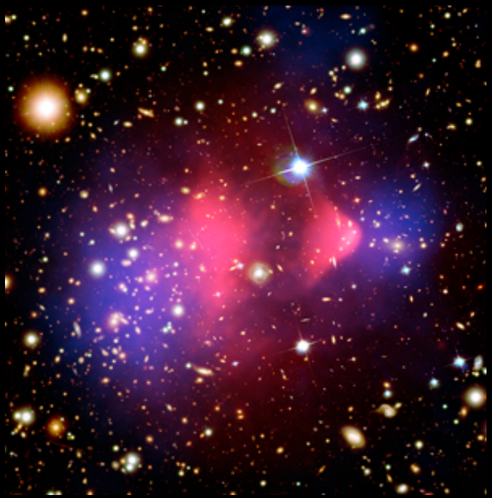
CMB



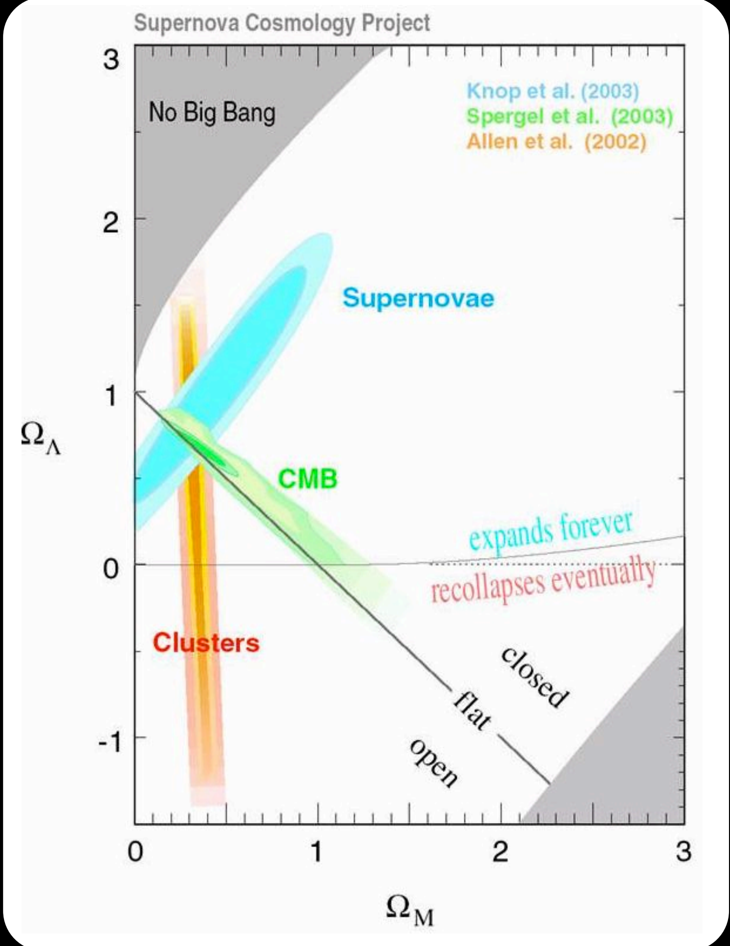
Supernova



Structure



Lensing

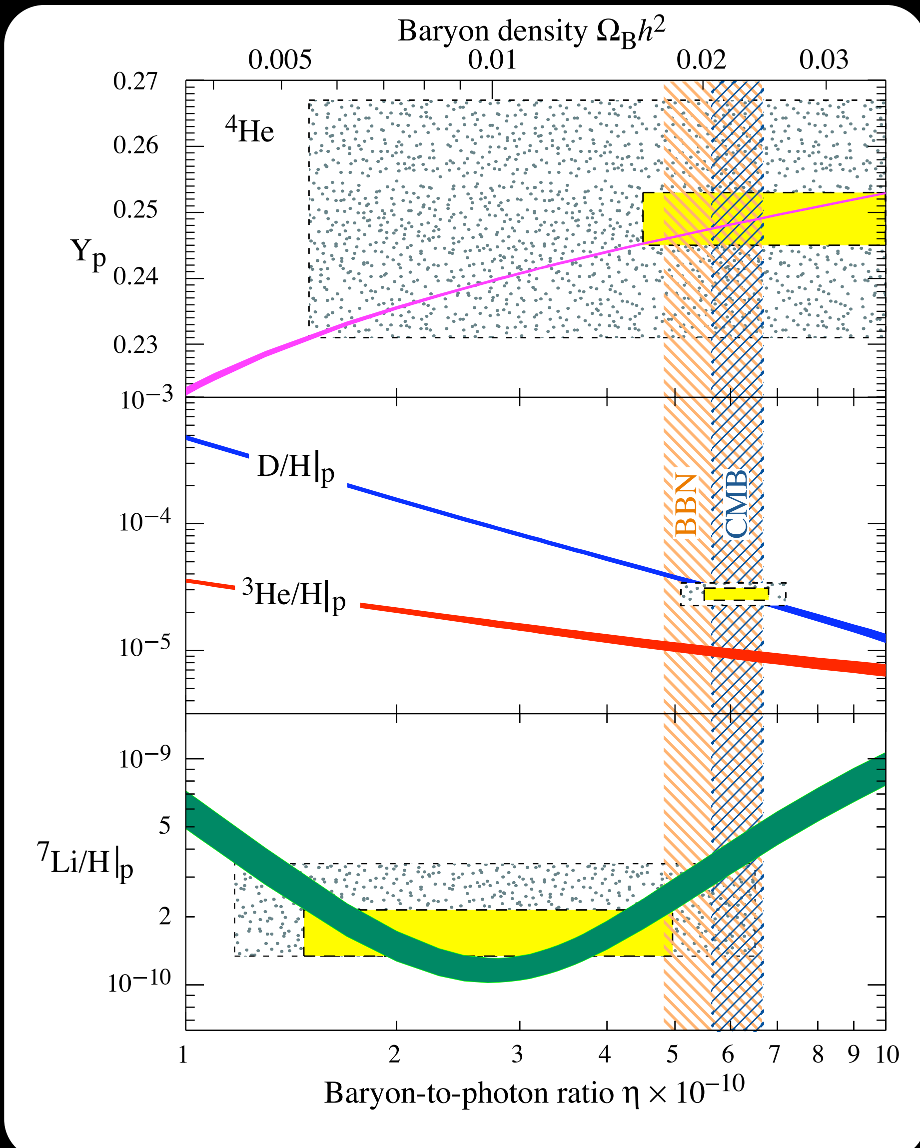


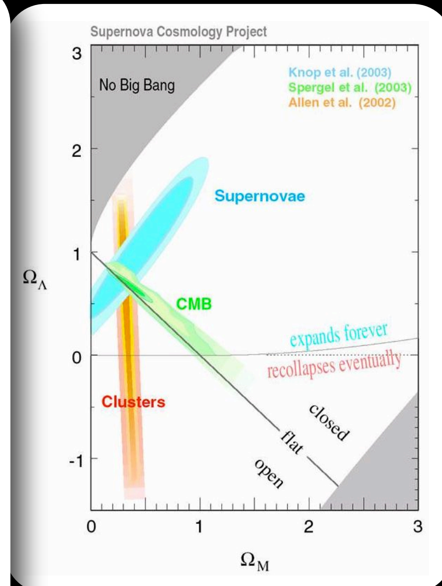
So what is Dark Matter?

“Cold Dark Matter: An Exploded View” by Cornelia Parker

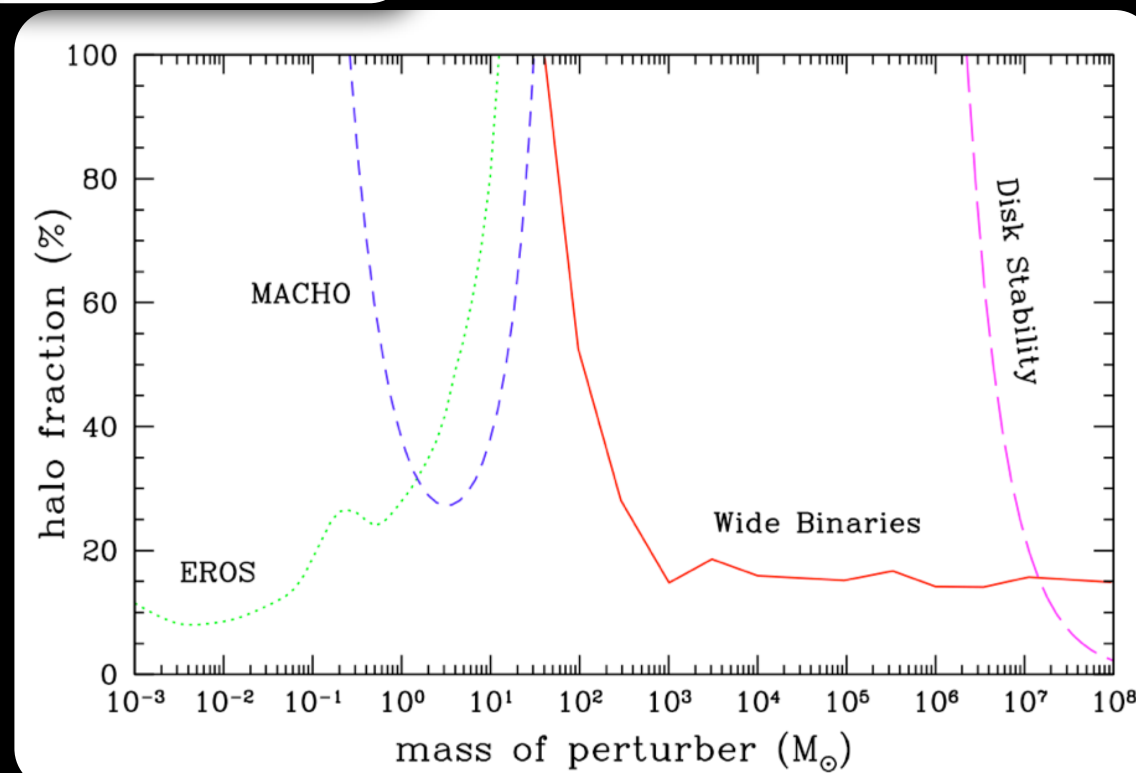
- As particle physicists, we need to know how dark matter fits into a particle description of Nature.
- What do we know about it?
  - Dark (neutral)
  - Massive (cold/non-relativistic)
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).
- Nothing in the Standard Model of particle physics fits the description.

Not Ordinary Matter





Nucleosynthesis determines the density of baryons at early times; the amount of baryonic matter required is far smaller than the total quantity of matter.



Primordial black holes remain a possible candidate, but would need some kind of mechanism to explain their production and mass distribution.

The Dark Matter Questionnaire

- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

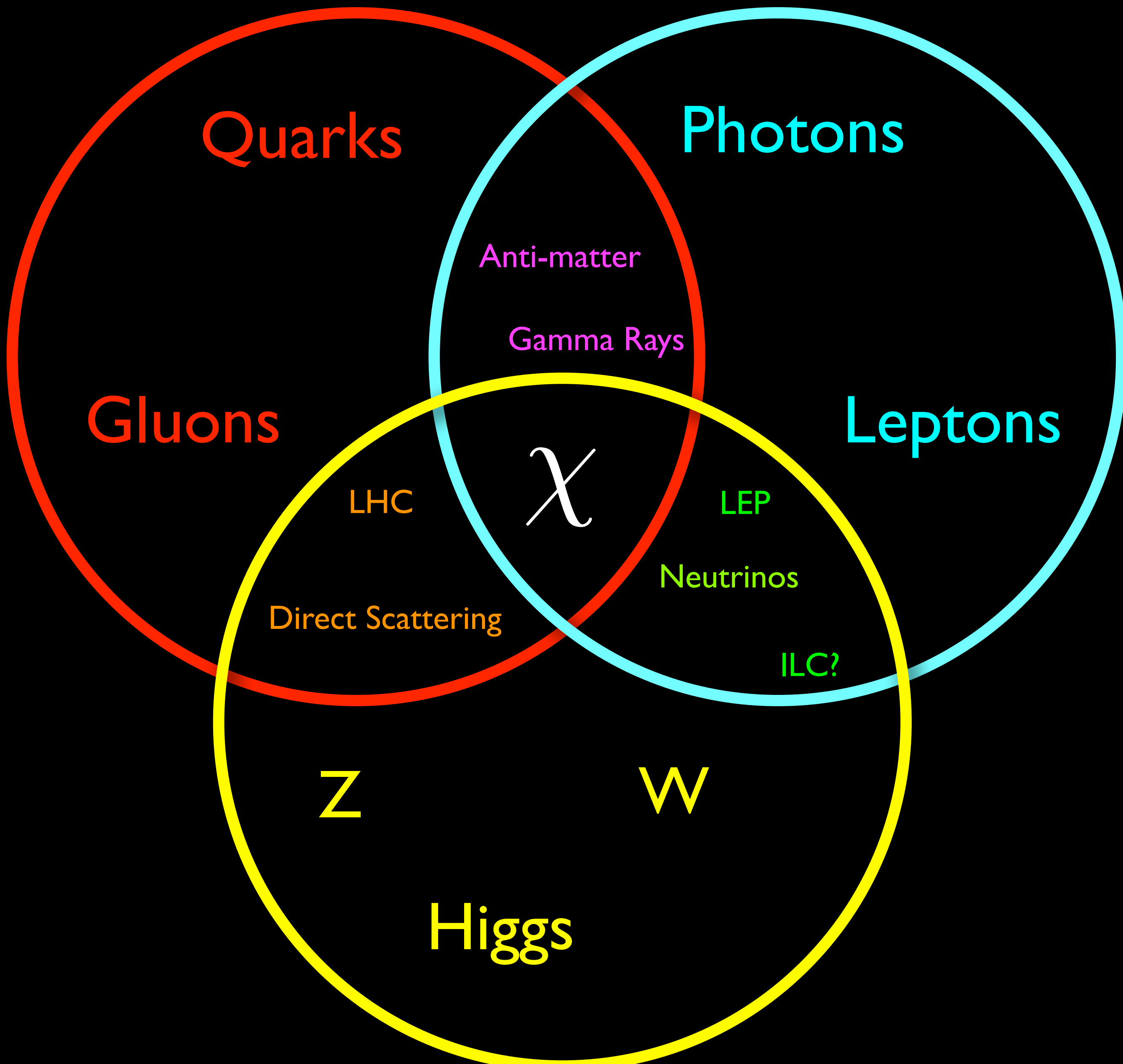
Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

Thermal Relic?

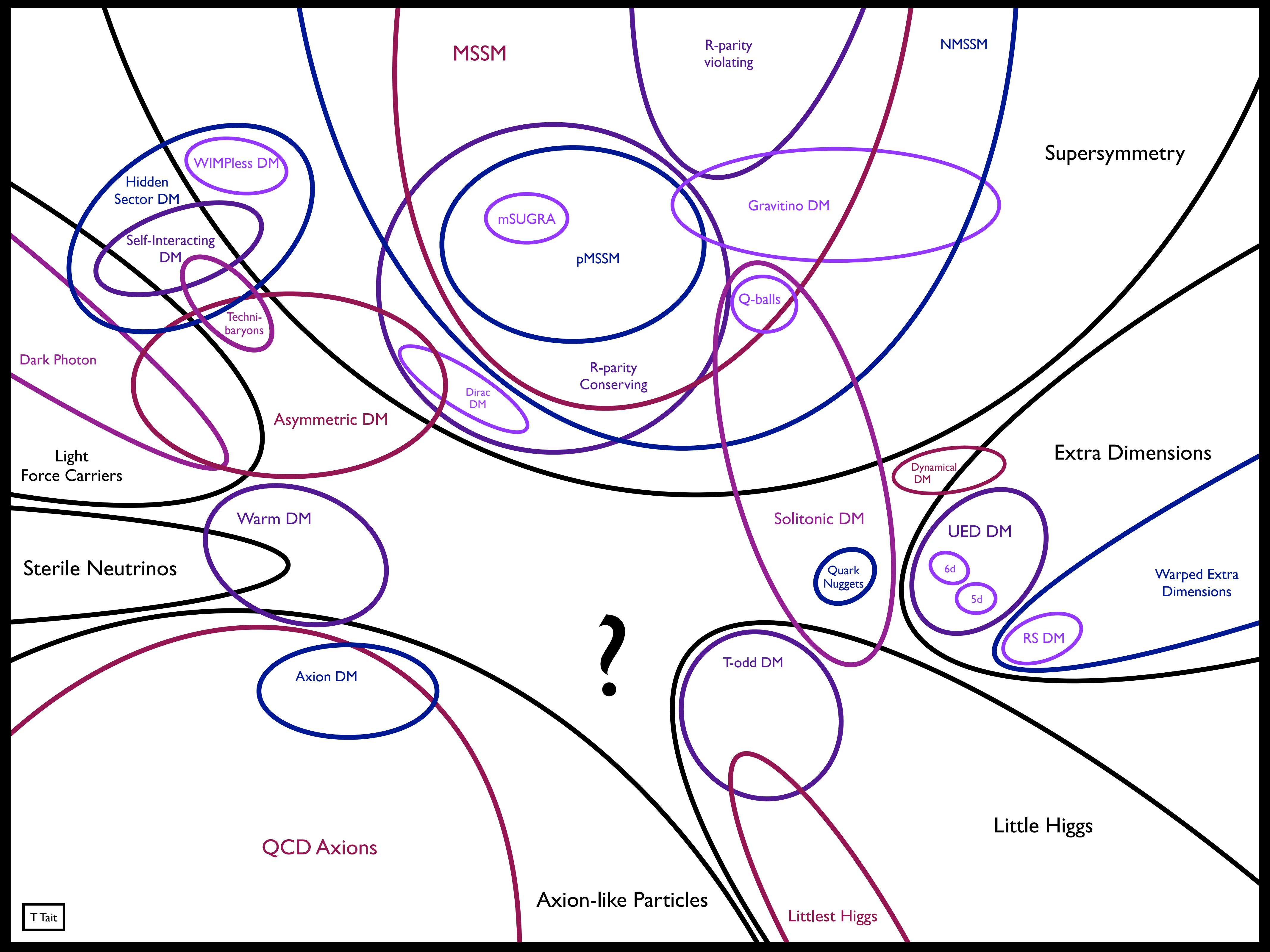
- ☐ Yes ☐ No

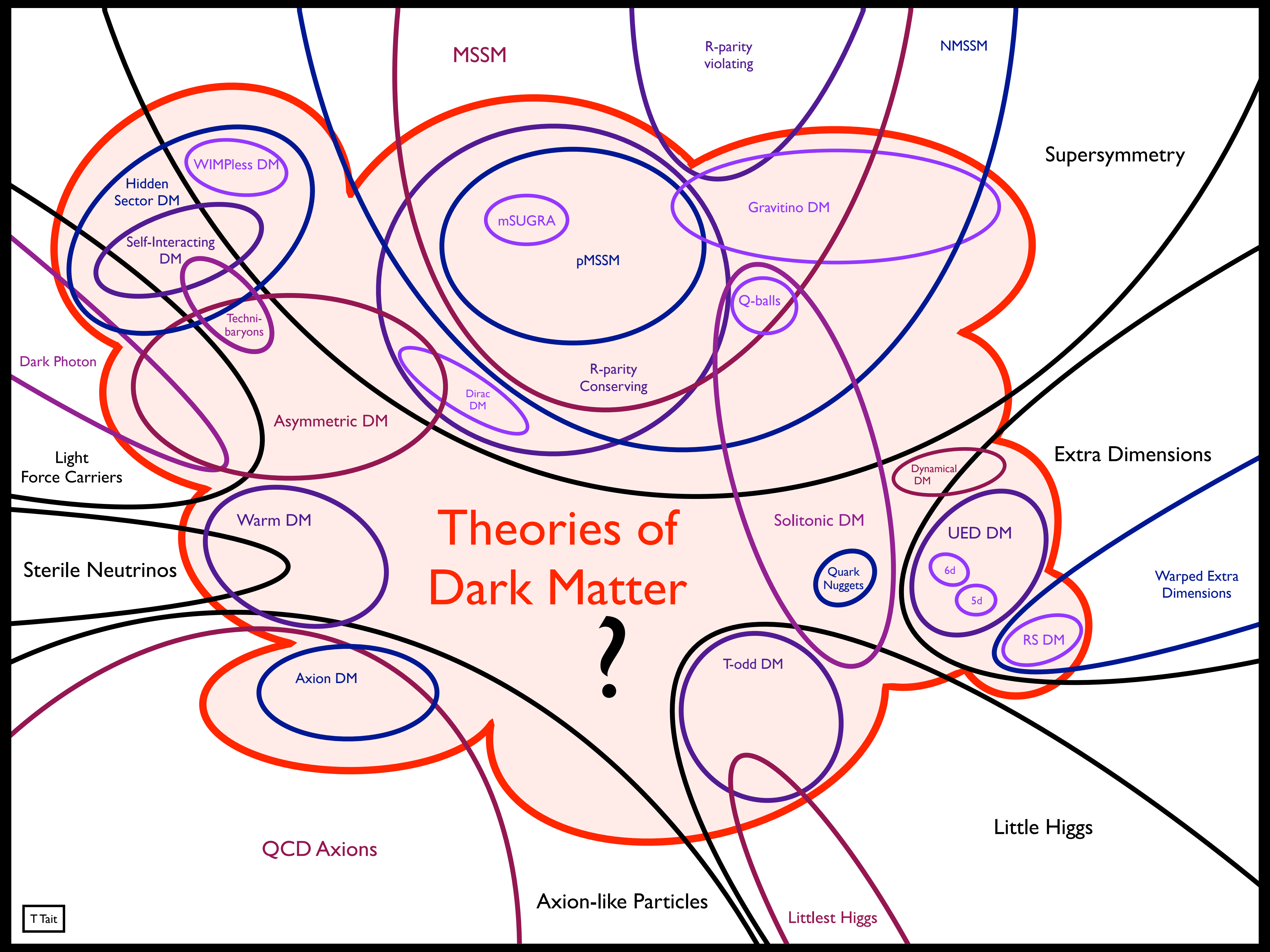
Map of DM-SM Interactions



Ultimately, we need to fill out the questionnaire experimentally. But as we try to relate the results of experiments to one another and unravel the deeper theoretical underpinning, we need at least some kind of theoretical framework in which to cast our progress.

What could the theory be?
No lack of possibilities...


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
?
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait



MSSM
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violating
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baryons
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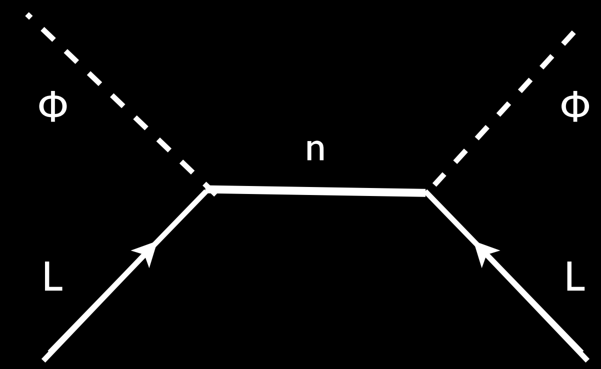
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

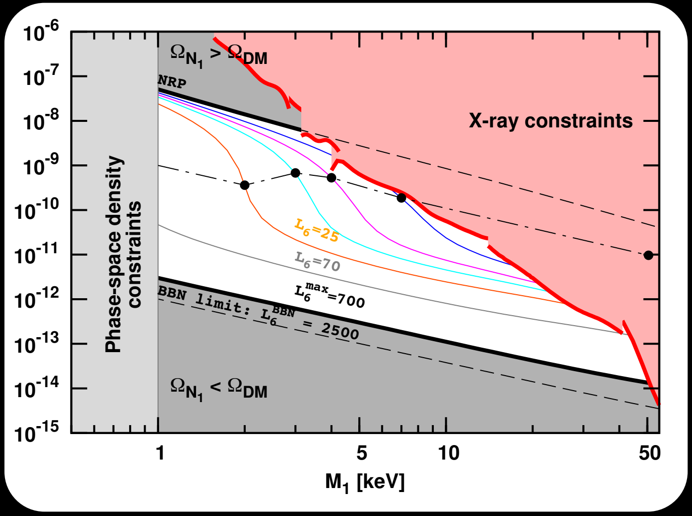
A Dizzying Array...

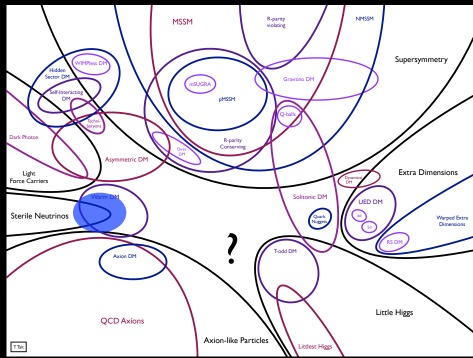
- Every theory on the previous slide contains an interesting, worthy vision for dark matter. And I am sure some are probably missing...
- Any of them could be the truth, or contain an element of the truth. We need to be prepared.
- There are also far far too many for me to go through them in any detail. I will focus my discussion on three broad categories:
  - Axions, and axion-like particles
  - Sterile Neutrinos
  - Weakly Interacting Massive Particles (WIMPs)
- The relevant Snowmass CF reports (CF1,2, 3, 4 and 6) contain a lot of very useful discussion of the details which I will not have time to address here, including (more) discussion of many theories.

Sterile Neutrino DM

- Dark matter may be connected to one of the other incontrovertible signals of physics beyond the SM: neutrino masses.
- The simplest way to generate neutrino masses in the SM is to add some number of gauge singlet fermions to play the role of the right-handed neutrinos.
- If the additional states are light and not strongly mixed with the active neutrinos (as required by precision EW data), they can be stable on the scale of the age of the Universe and play the role of dark matter.
- Arriving at the right amount of dark matter typically requires delicately choosing the mass and mixing angle, or invoking some other new physics.

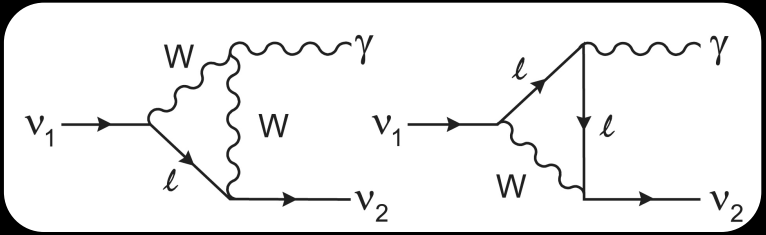


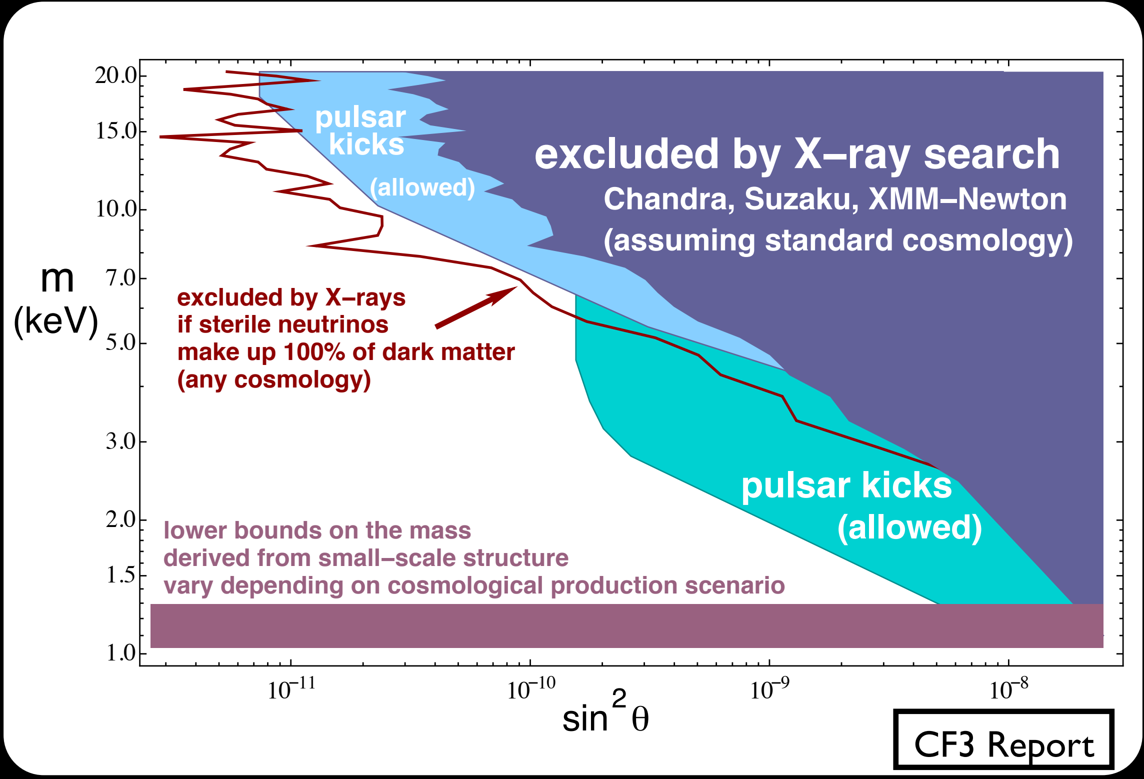




Sterile Neutrino DM

- Structure formation requires masses greater than a few keV to avoid washing out small scale structures.
- Though rare, sterile neutrinos can decay into ordinary neutrinos and a photon, resulting in (mono-energetic) keV energy photons.
- Constraints from the lack of observation of such a signal put limits in the plane of the mass versus the mixing angle.





Axion Dark Matter

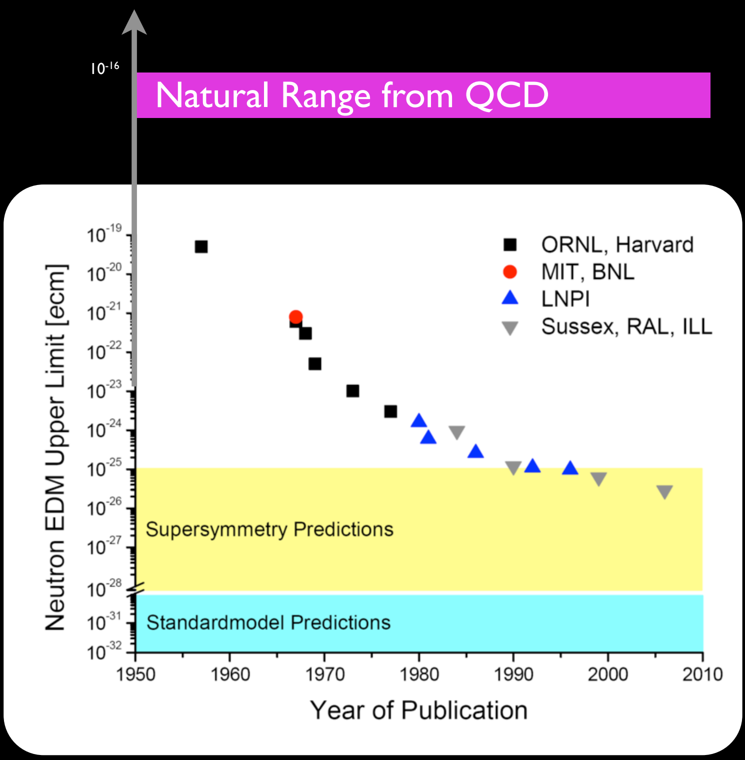
- The axion is motivated by the strong CP-problem, where the QCD θ term is cancelled by introducing a scalar field -- the QCD axion.

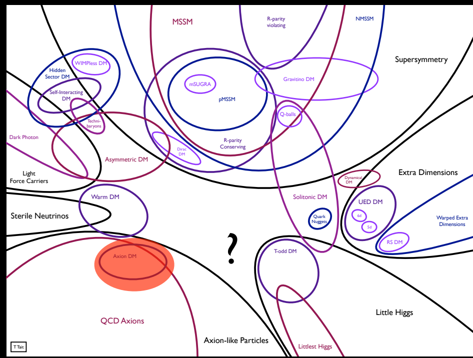
- The axion's mass and coupling are determined by virtue of its being a pseudo-Goldstone boson and are characterized by the energy scale $f_a > 10^9$ GeV.

$$m_a \sim f_\pi / f_a \times m_\pi$$

- The axion is unstable, but its tiny mass and weak couplings conspire to predict that for much of the viable parameter space its lifetime is much greater than the age of the Universe itself.

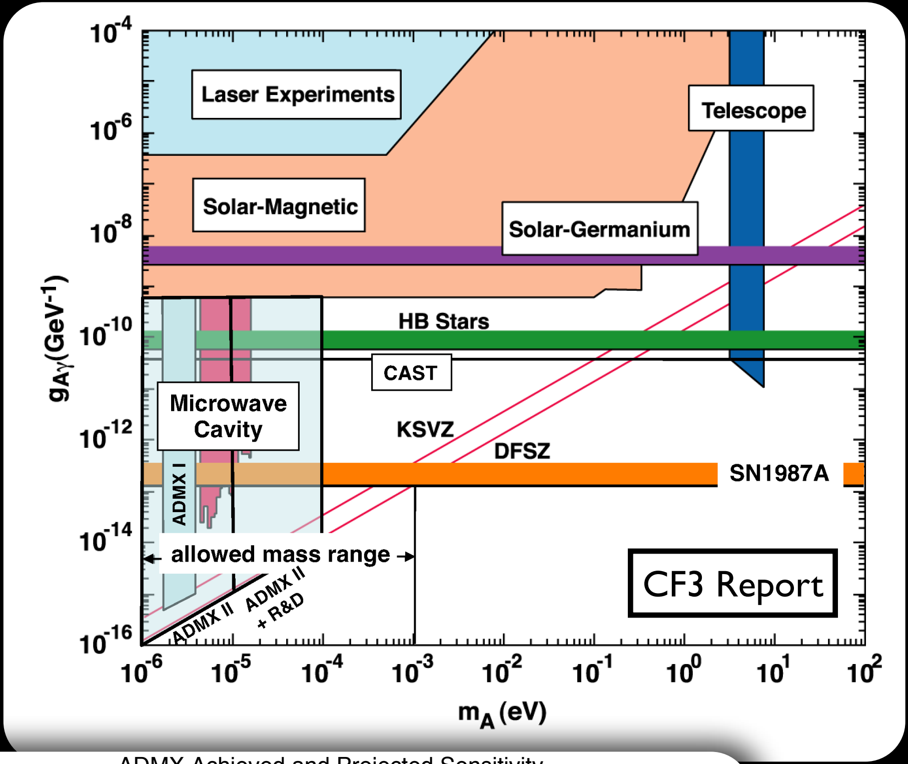
- More generally, string theories often contain axion-like particles which are long-lived and can play the role of dark matter but have less tight correlations between their masses and couplings.

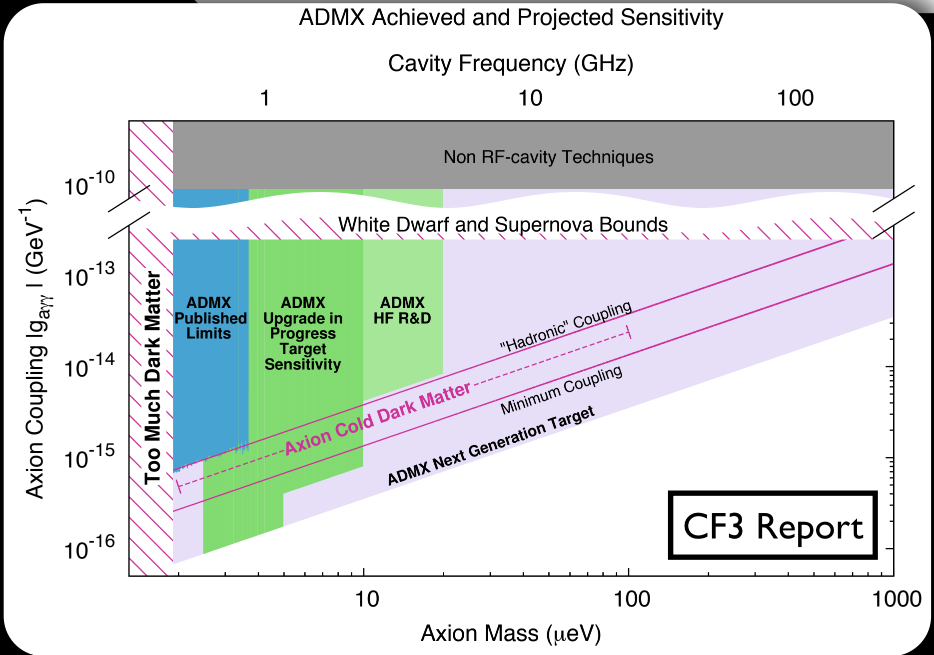




Axion Dark Matter

- The axion has a model-dependent coupling to electromagnetic fields that is somewhat smaller than $1 / f_a$.
- There is a rich and varied program of axion searches based on this coupling.
- One particular search looks for DM axions converting into EM signals in the presence of a strong background magnetic field.
- Other very interesting new ideas are to look for time variation in the neutron EDM or the induced current in an LC circuit.

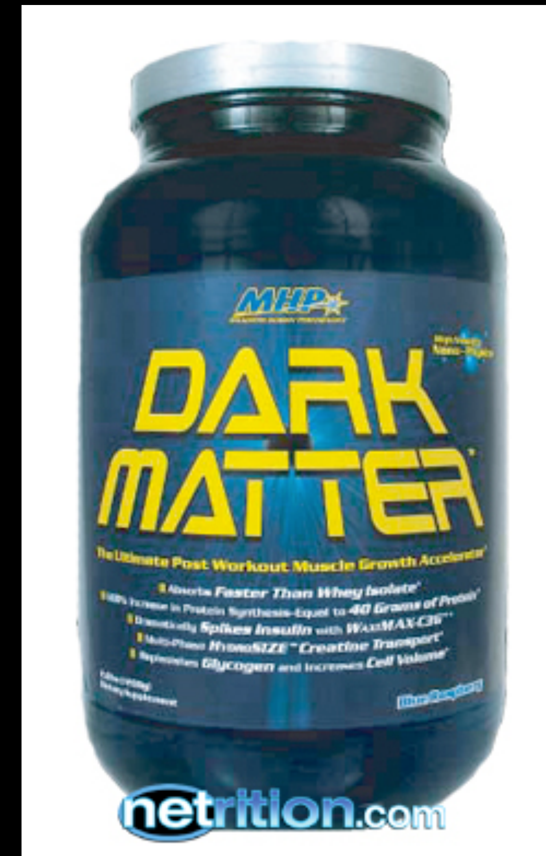




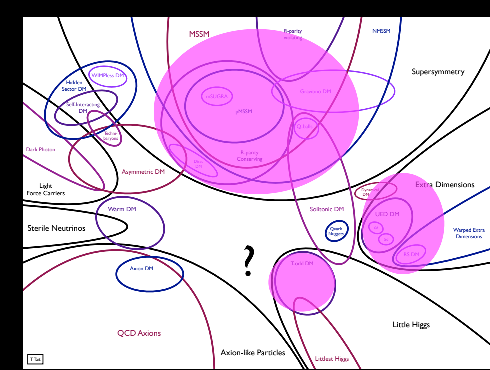
1306.6088 & 1310.8545

WIMPs

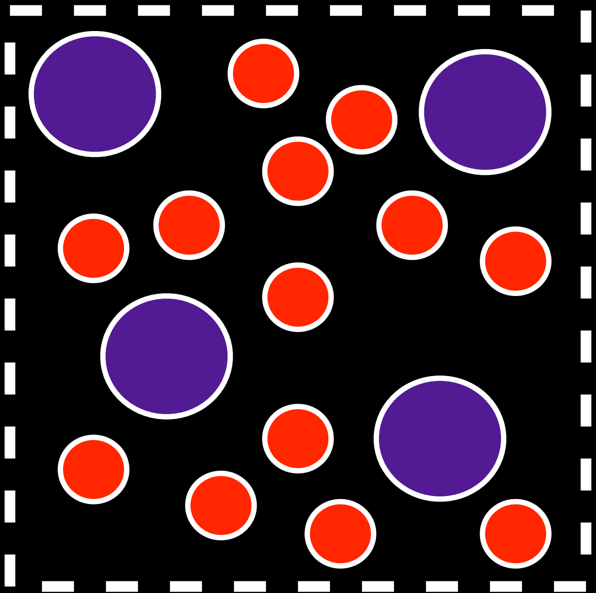
- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally can account for the amount of dark matter we observe in the Universe.
  - WIMPs automatically occur in many models of physics beyond the Standard Model, such as supersymmetric extensions with R-parity, extra-dimensional theories with KK-parity, and natural theories of electroweak symmetry breaking with T-parity.
- I will try to avoid any further discussion of specific WIMP theories. Most of the phenomena we will see are represented to different degrees in any of the commonly considered theories of WIMPs.



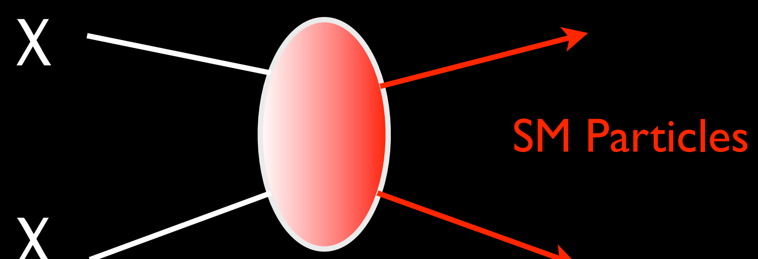
$59.99 for 20 servings
Available in Blue Raspberry, Fruit Punch, and Grape flavors....



The WIMP Miracle



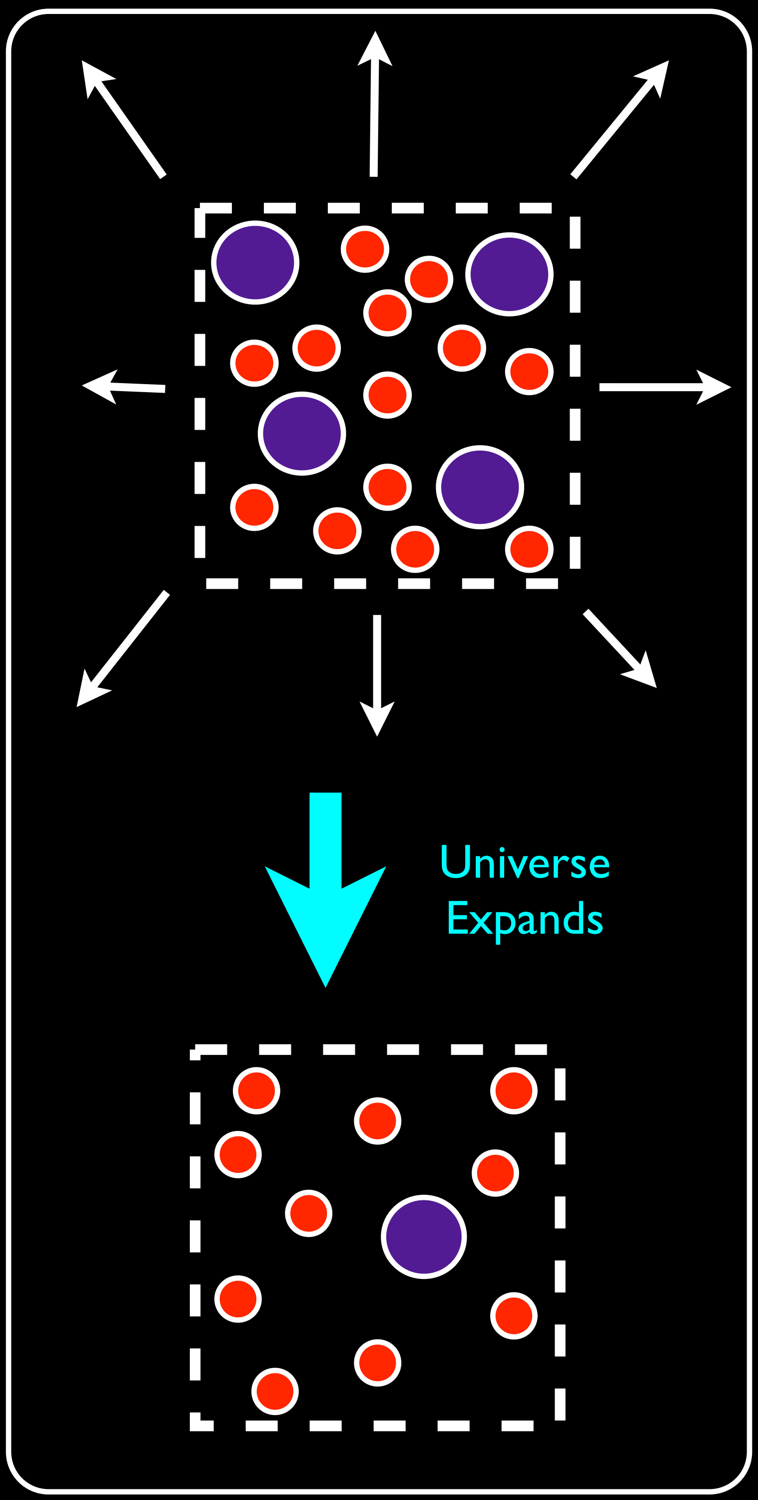
- One of the primary motivations for WIMPs is the "WIMP miracle", an attractive picture explaining the density of dark matter in the Universe today.
- The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.
- Equilibrium is maintained by scattering of WIMPs into SM particles, XX -> SM.
- While in equilibrium at temperatures below its mass, the WIMP number density follows the Boltzmann distribution:



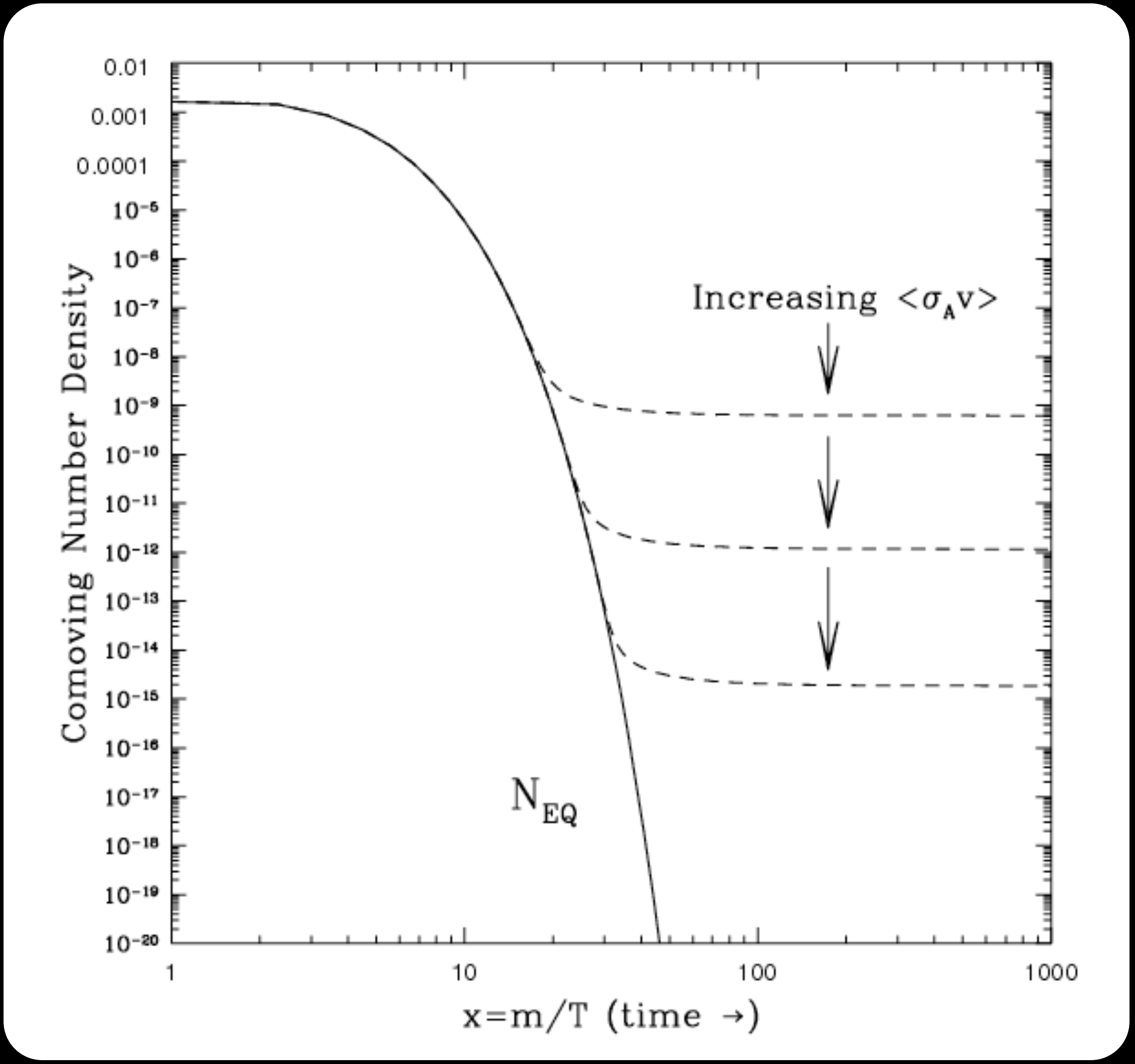
$$n_{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} \mathrm{Exp}\left[-m/T \right]$$

Freeze-Out

- Expansion of the Universe eventually results in a loss of equilibrium.
- At the "freeze-out" temperature, the WIMPs are sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- The temperature at which this occurs depends quite sensitively on $\sigma(\chi\chi \to \mathrm{SM})$: more strongly interacting WIMPs will stay in equilibrium longer, and thus end up with a smaller relic density than more weakly interacting WIMPs.



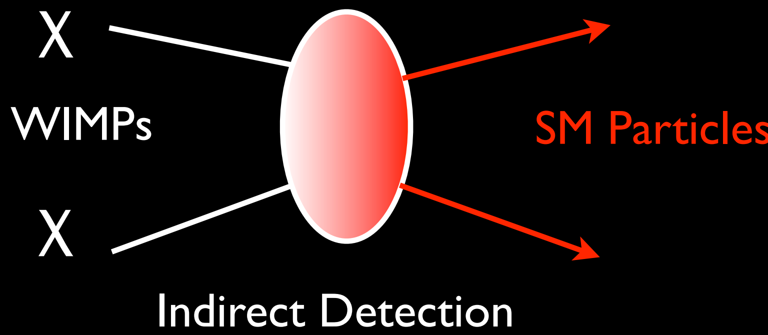
Relic Density

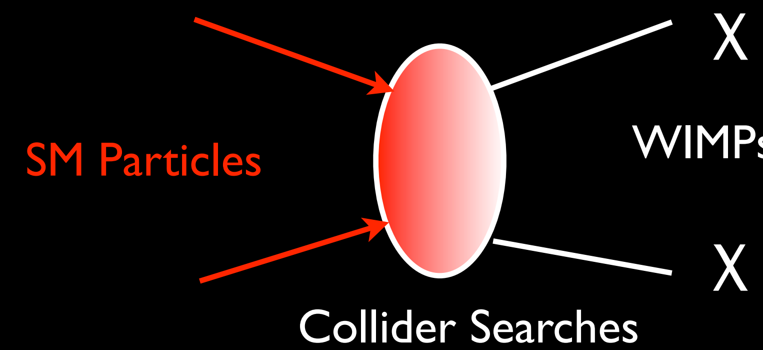


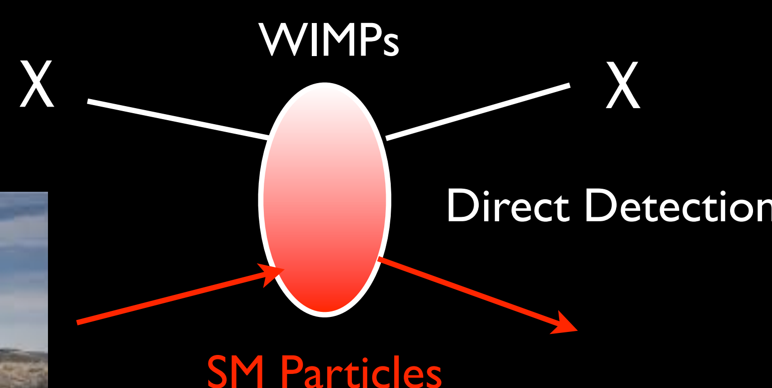
x=m/T increasing
is
T decreasing
is
time increasing

- The observed quantity of dark matter is suggestive of a cross section for annihilation into SM particles: $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ cm^3/s, roughly independently of the mass of the dark matter.

Particle Probes of WIMPs



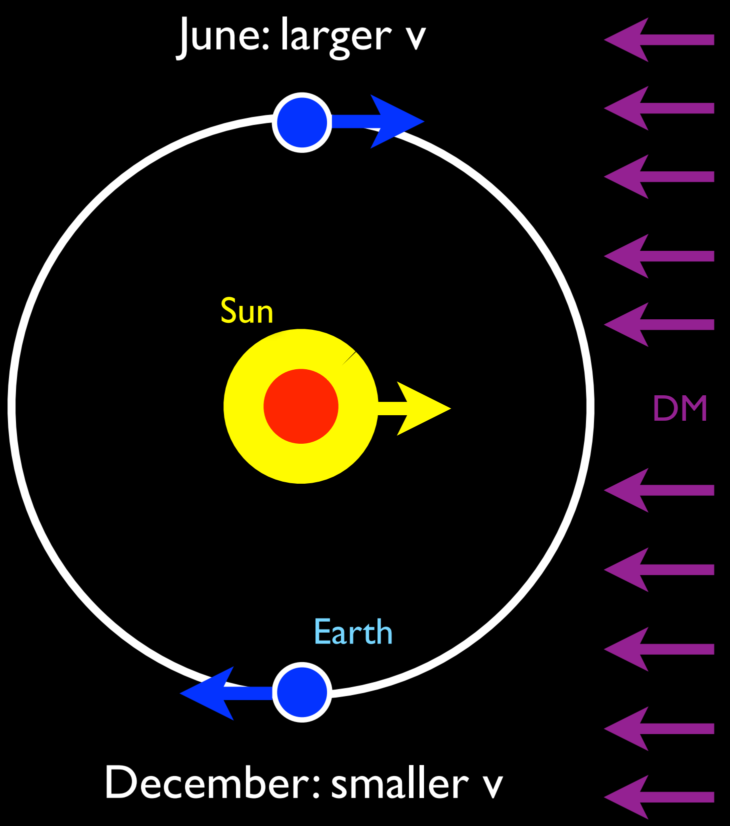


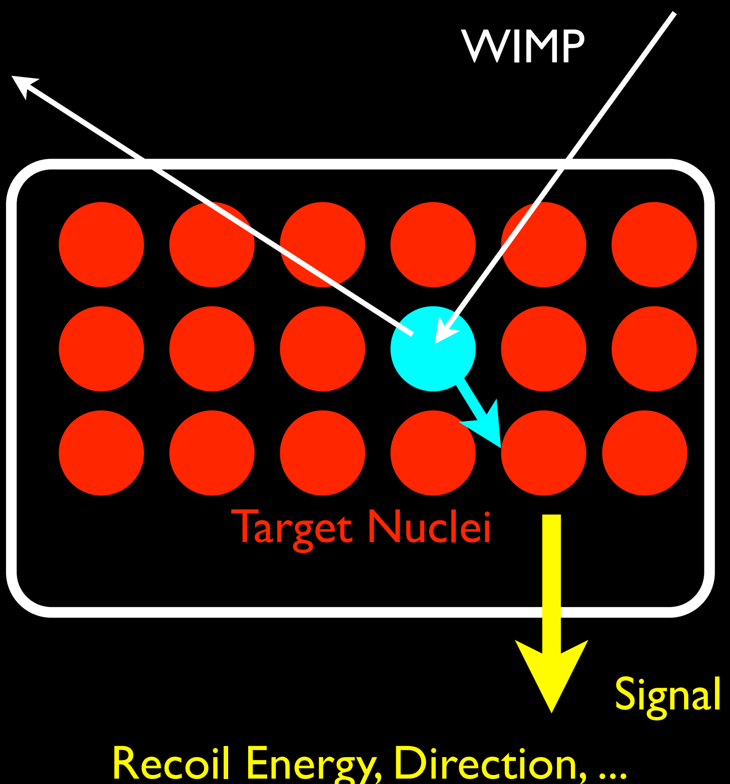


- The common feature of particle searches for WIMPs is that all of them are determined by how WIMPs interact with the Standard Model.

Direct Detection

- Direct detection searches for dark matter scattering off of terrestrial targets.
- Amazing progress has shown that backgrounds can be rejected to a very high degree.
- Handles include the recoil energy spectrum, distribution of recoil direction, and modulation of the signal with time.

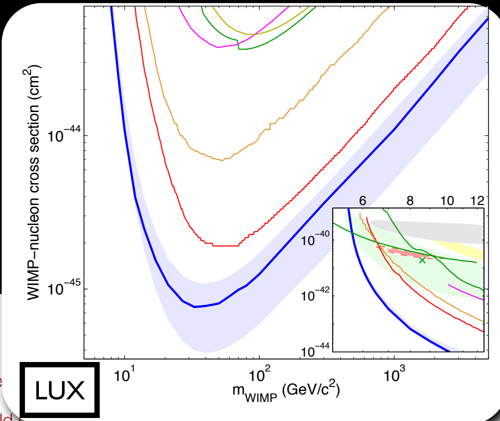




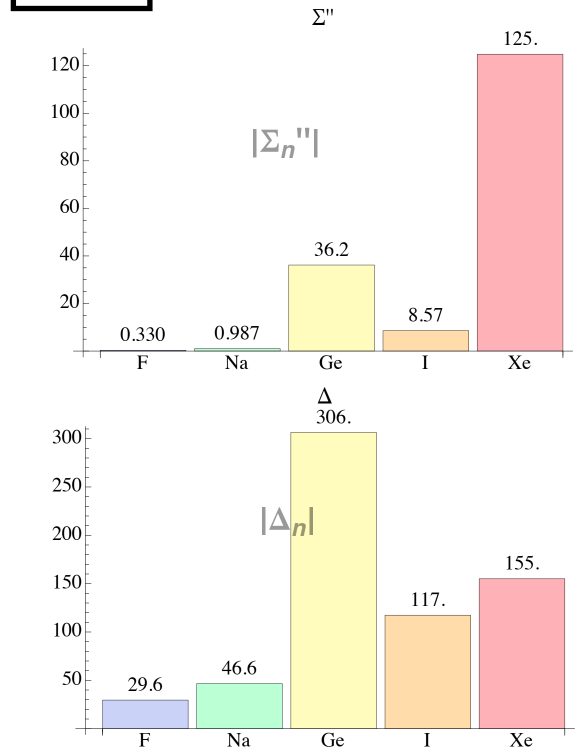
- One challenge for the future is improving sensitivity to low mass dark matter (which carries less momentum and results in smaller signals).
- Eventually experiments will reach sensitivity to background neutrinos, which are independently interesting but will complicate WIMP searches.

Direct Detection

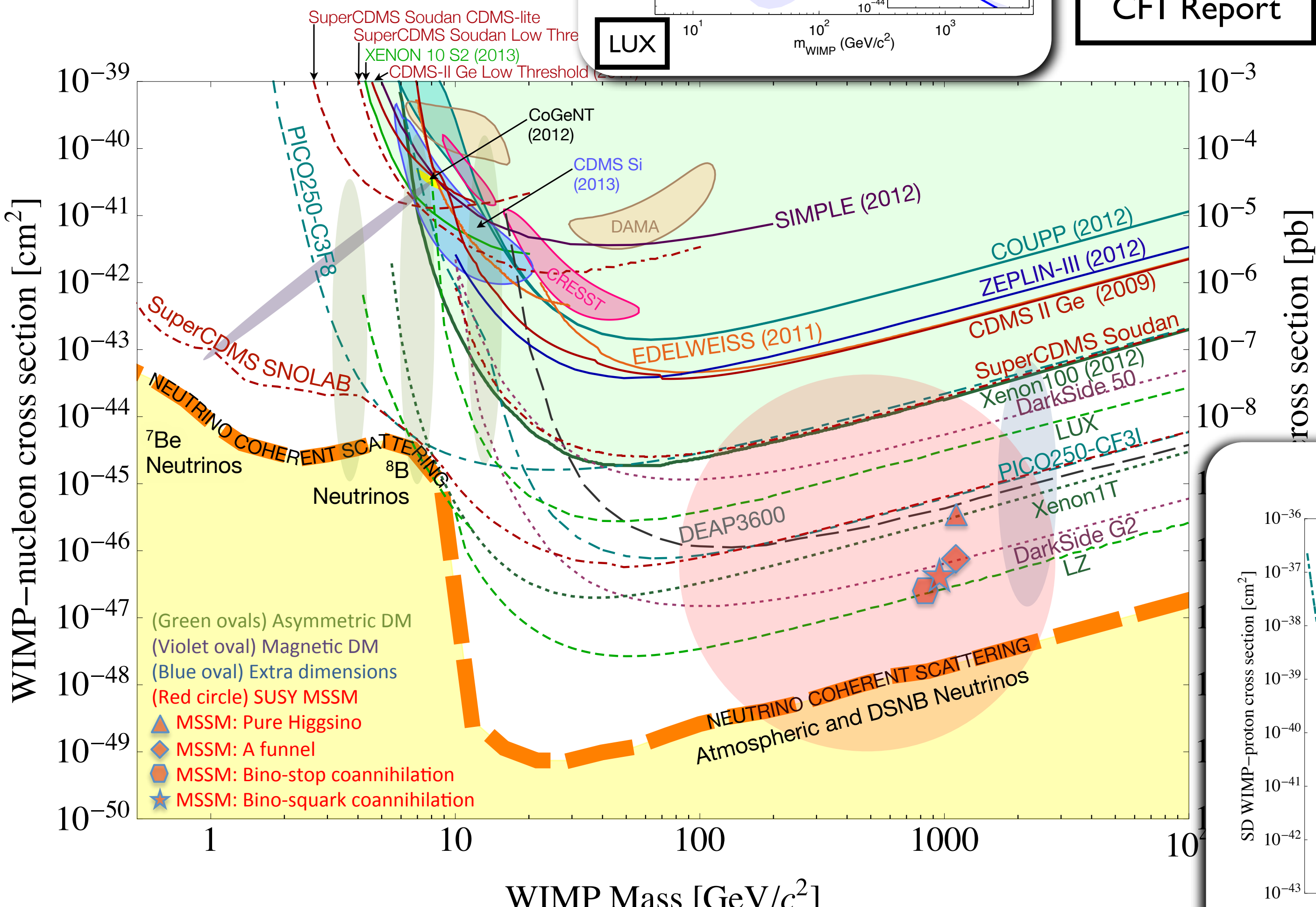
LUX



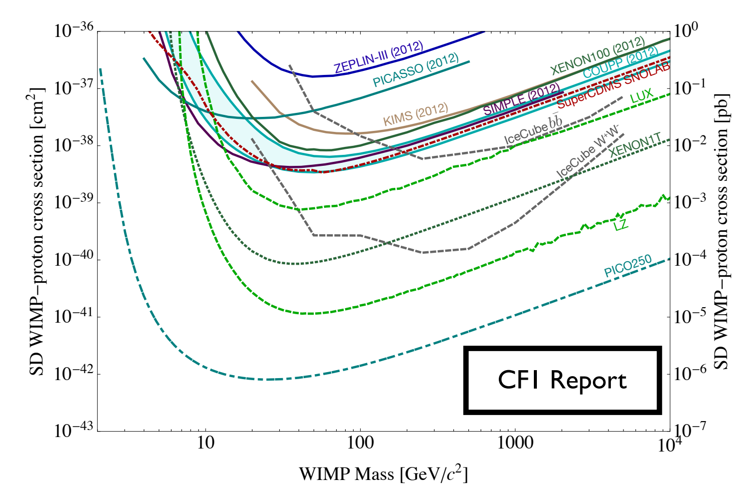
1211.2818



CF1 Report



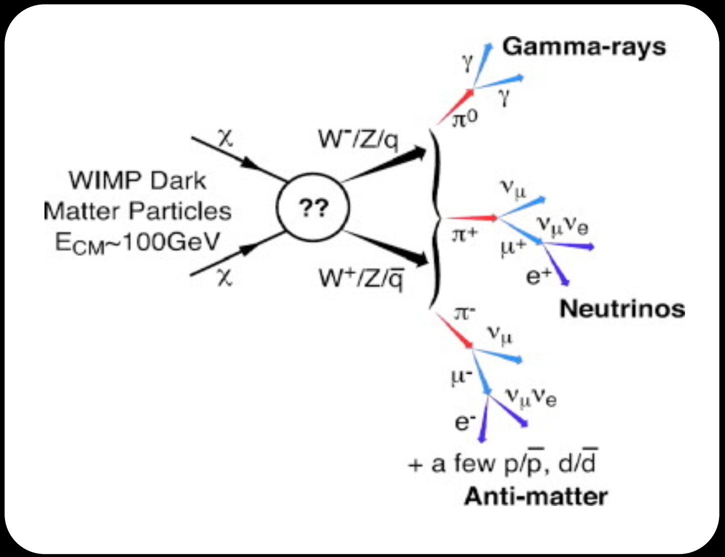
(Missing the recent LUX update)

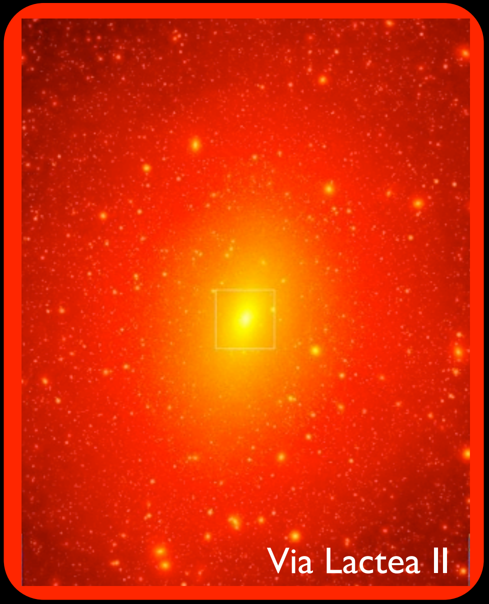


CF1 Report

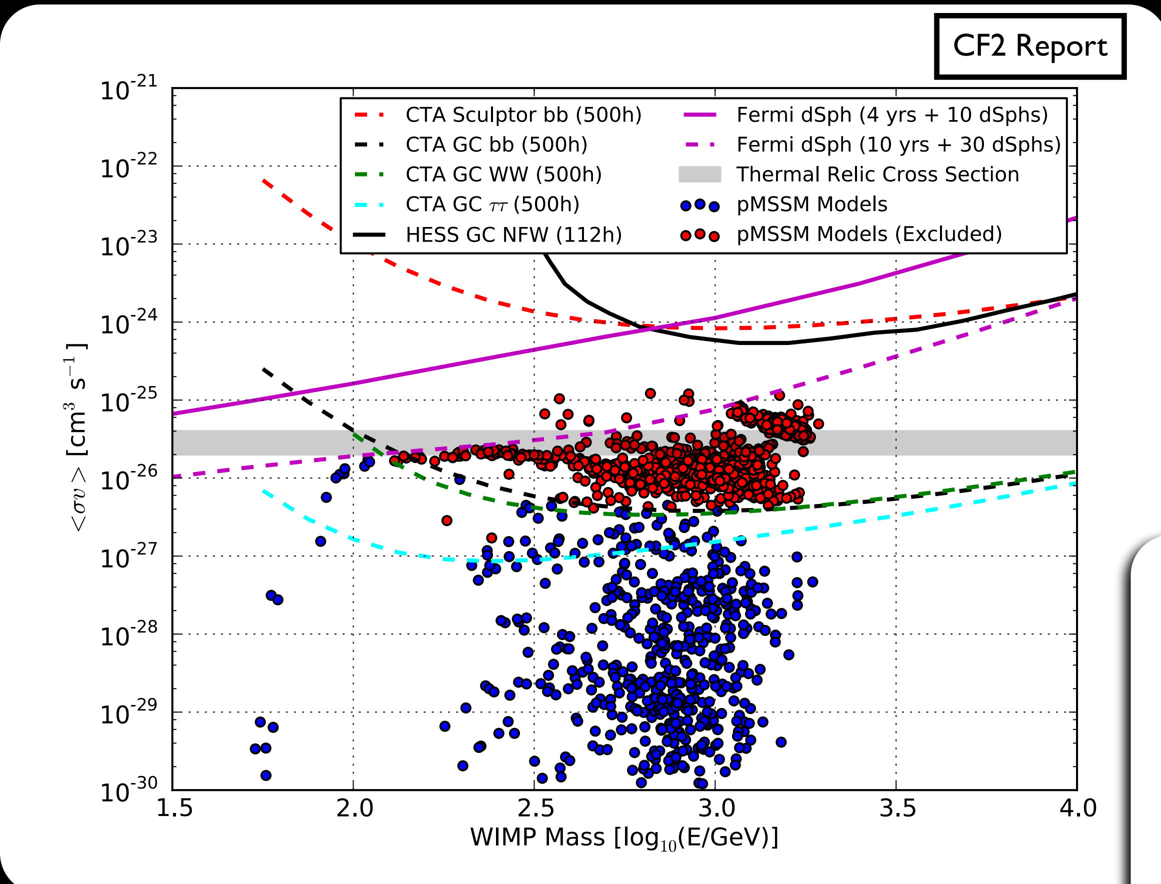
Indirect Detection

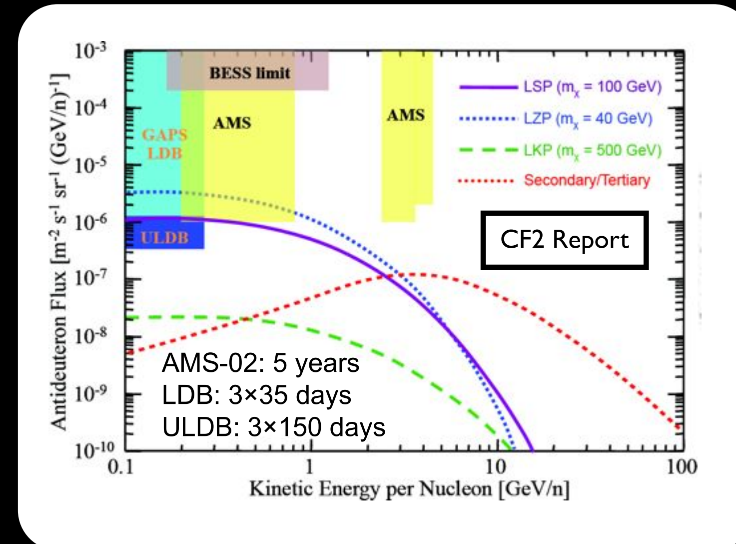
- Indirect detection looks for distinctive products of WIMP annihilation.
- High energy gamma rays, neutrinos, and anti-matter are all interesting messengers that could reveal the presence of dark matter annihilations.
    - Gamma rays: point back to their source and have relatively little propagation uncertainty in the galaxy.
    - Neutrinos: arrive essentially unchanged from galactic sources.
    - Anti-matter: very distinctive signal, but lose direction and energy en route.
- Challenges include large and often poorly understood backgrounds and uncertainties in the dark matter distribution.

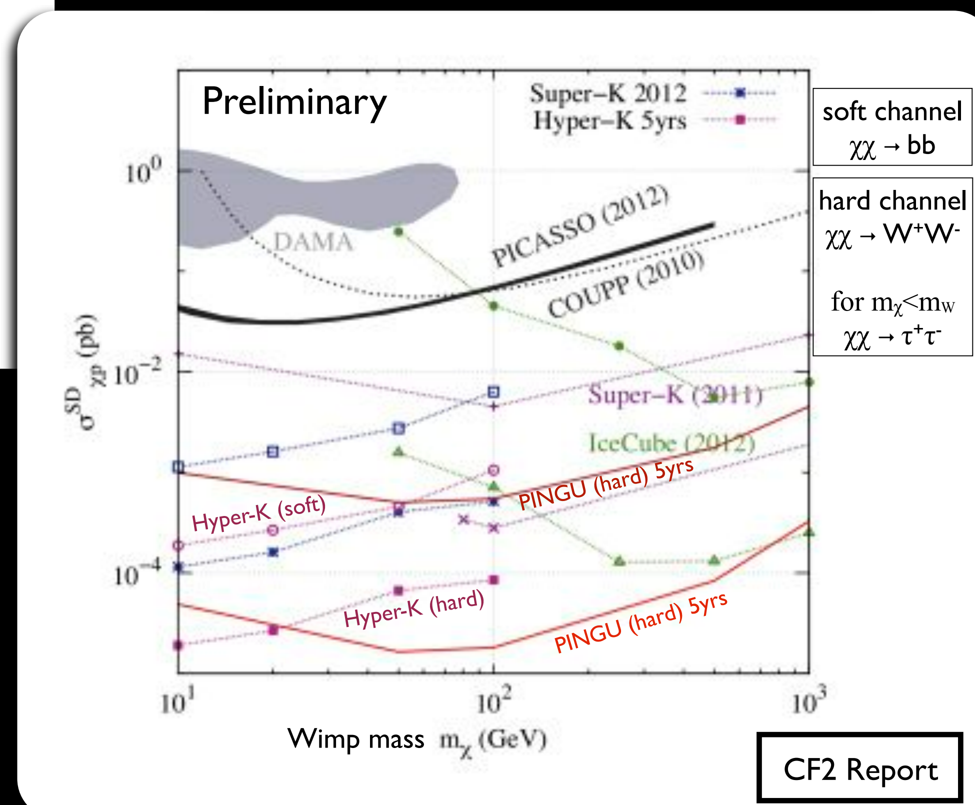




Indirect Detection

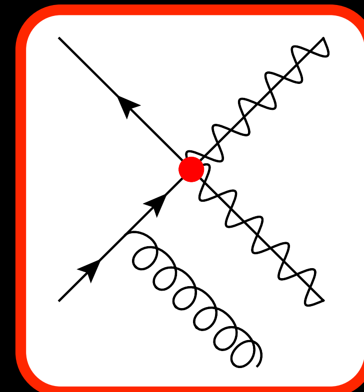


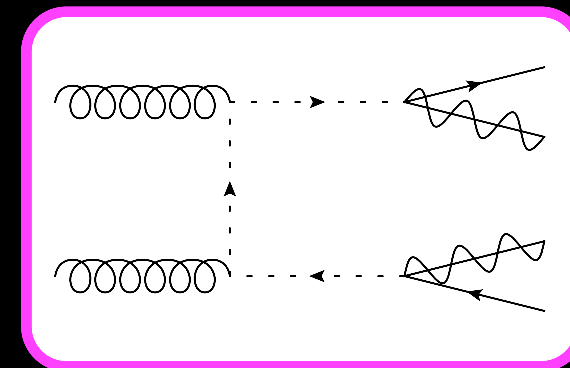


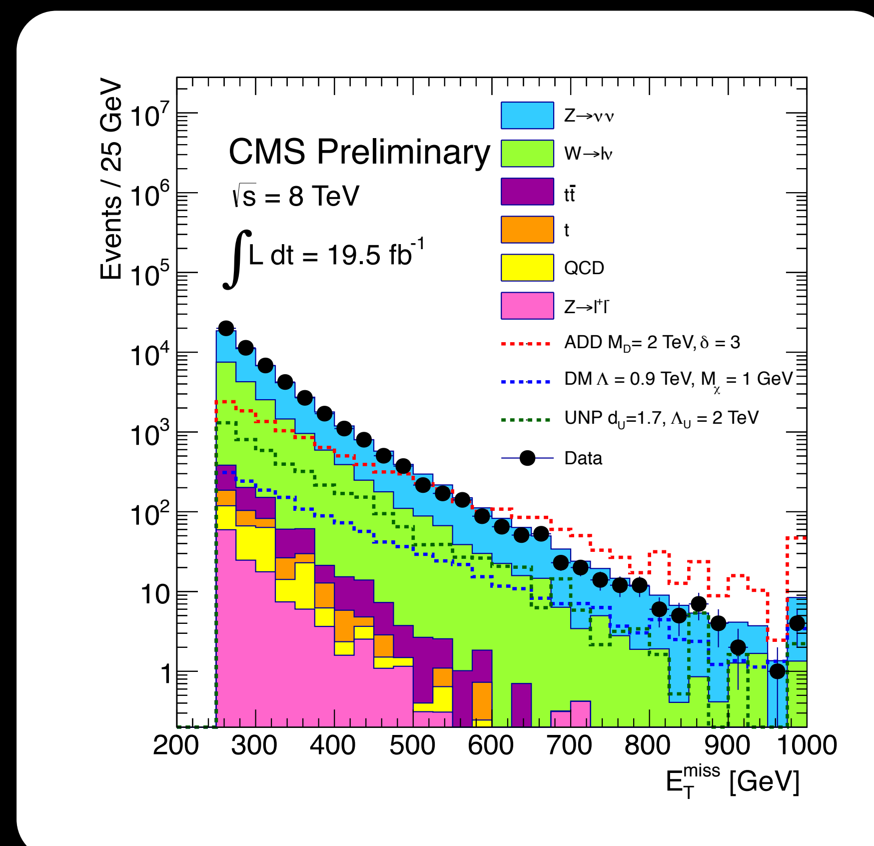


Colliders

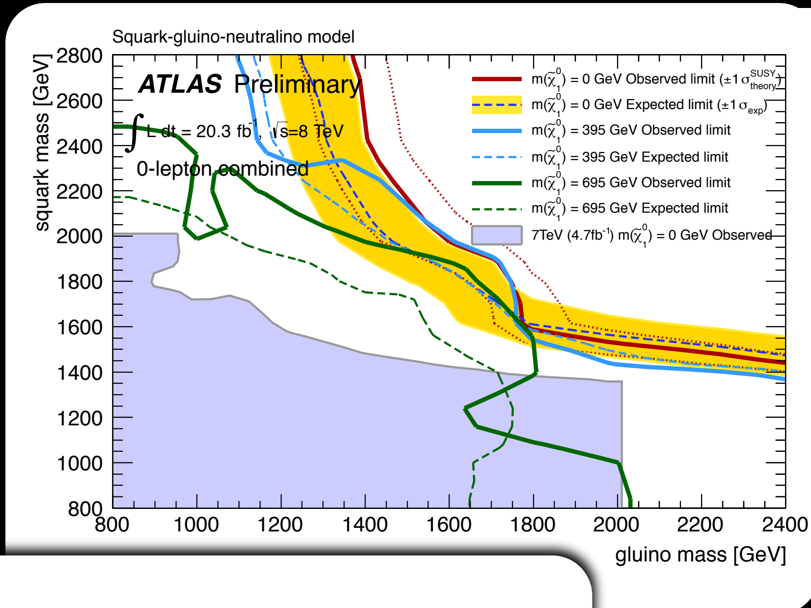
- High energy colliders offer the opportunity to produce dark matter in the laboratory.
- Since dark matter typically does not interact with a collider detector in transit, it reveals its presence as an imbalance in momentum conservation.
- Colliders have strengths in their exquisite control over the initial state, and well understood backgrounds.
- An important challenge is the fact that any observation of missing momentum will not be uniquely connected to dark matter: particles with lifetimes of ~1 s and ~14 Gyr are essentially the same signature.



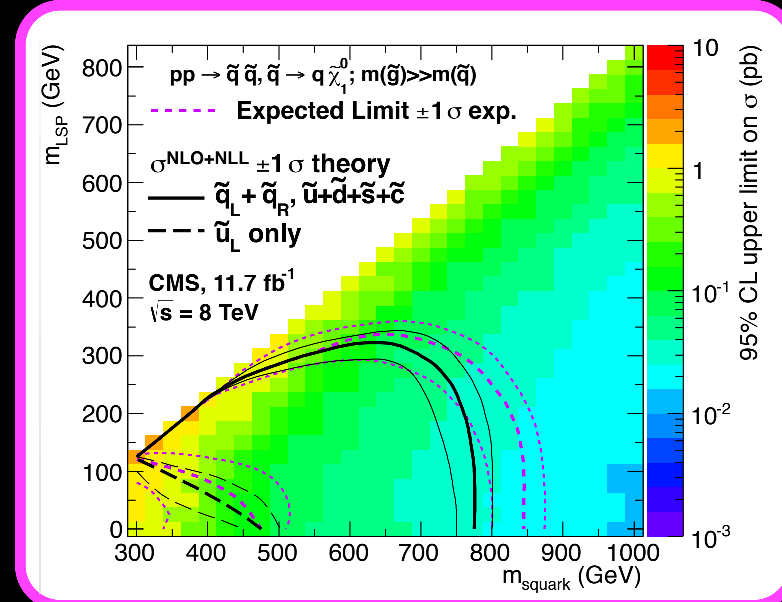




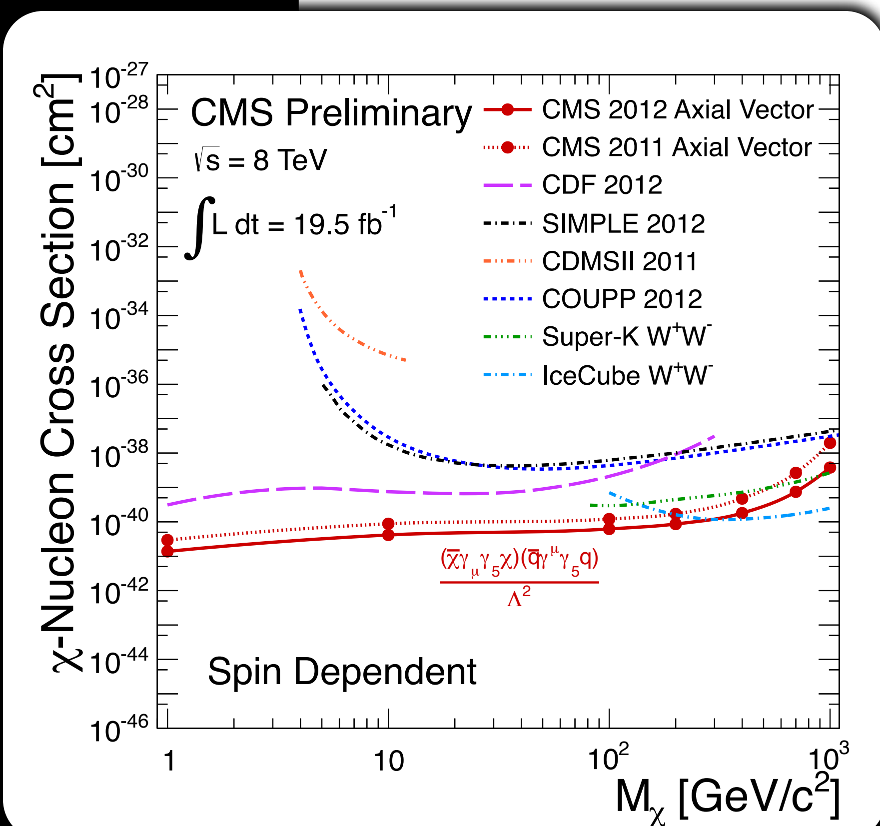
Colliders



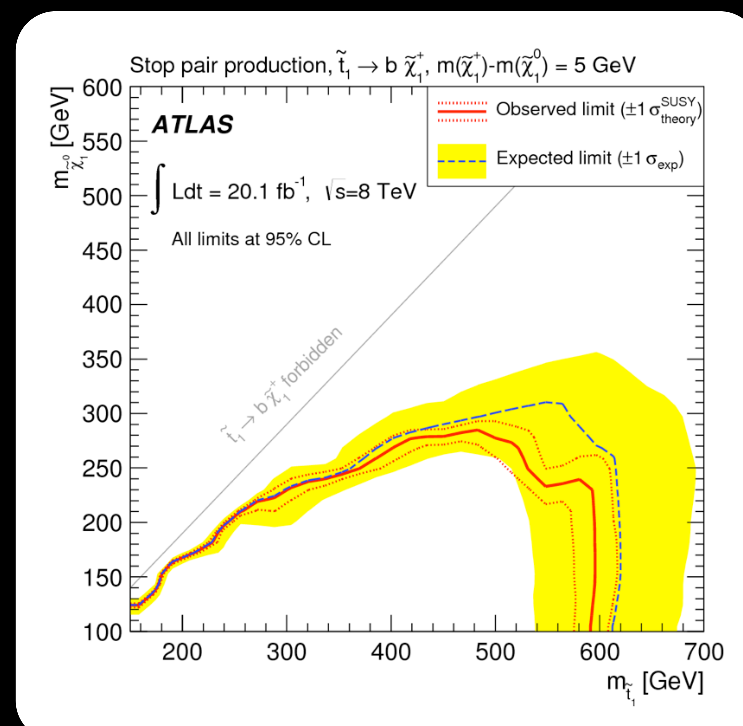
Squark-gluino-neutralino model
ATLAS Preliminary
∫L dt = 20.3 fb⁻¹, √s=8 TeV
0-lepton combined
m(χ̃⁰₁) = 0 GeV Observed limit (±1 σ theory SUSY)
m(χ̃⁰₁) = 0 GeV Expected limit (±1 σ exp)
m(χ̃⁰₁) = 395 GeV Observed limit
m(χ̃⁰₁) = 395 GeV Expected limit
m(χ̃⁰₁) = 695 GeV Observed limit
m(χ̃⁰₁) = 695 GeV Expected limit
7TeV (4.7fb⁻¹) m(χ̃⁰₁) = 0 GeV Observed
squark mass [GeV]
gluino mass [GeV]



pp → q̃ q̃, q̃ → q χ̃⁰₁; m(g̃)>>m(q̃)
Expected Limit ±1 σ exp.
σNLO+NLL ±1 σ theory
q̃L + q̃R, ũ+d̃+s̃+c̃
ũL only
CMS, 11.7 fb⁻¹
√s = 8 TeV
m_LSP (GeV)
m_squark (GeV)
95% CL upper limit on σ (pb)



CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb⁻¹
CMS 2012 Axial Vector
CMS 2011 Axial Vector
CDF 2012
SIMPLE 2012
CDMSII 2011
COUPP 2012
Super-K W⁺W⁻
IceCube W⁺W⁻
(χ̄γμγ5χ)(q̄γμγ5q) / Λ²
Spin Dependent
χ-Nucleon Cross Section [cm²]
Mχ [GeV/c²]

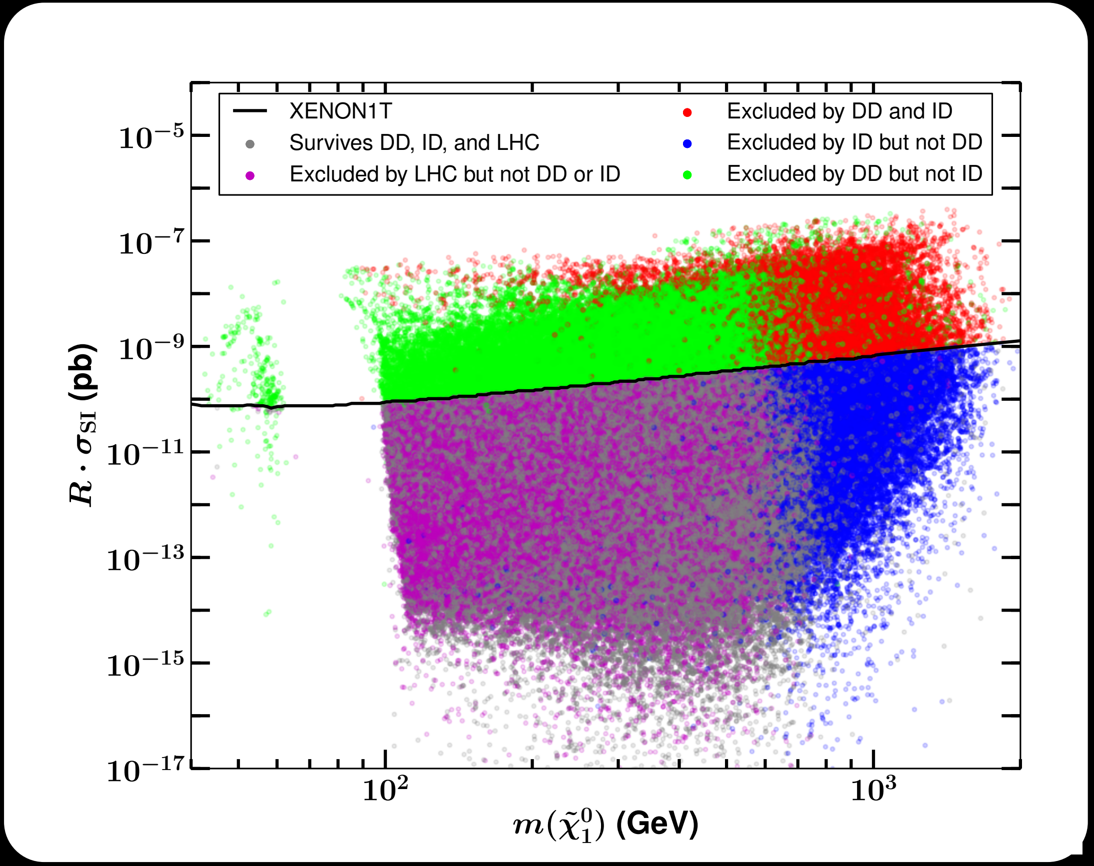


Stop pair production, t̃1 → b χ̃⁺1, m(χ̃⁺1)-m(χ̃⁰1) = 5 GeV
ATLAS
∫ Ldt = 20.1 fb⁻¹, √s=8 TeV
All limits at 95% CL
Observed limit (±1 σ theory SUSY)
Expected limit (±1 σ exp)
t̃1 → b χ̃⁺1 forbidden
m χ̃⁰1 [GeV]
m t̃1 [GeV]

pMSSM

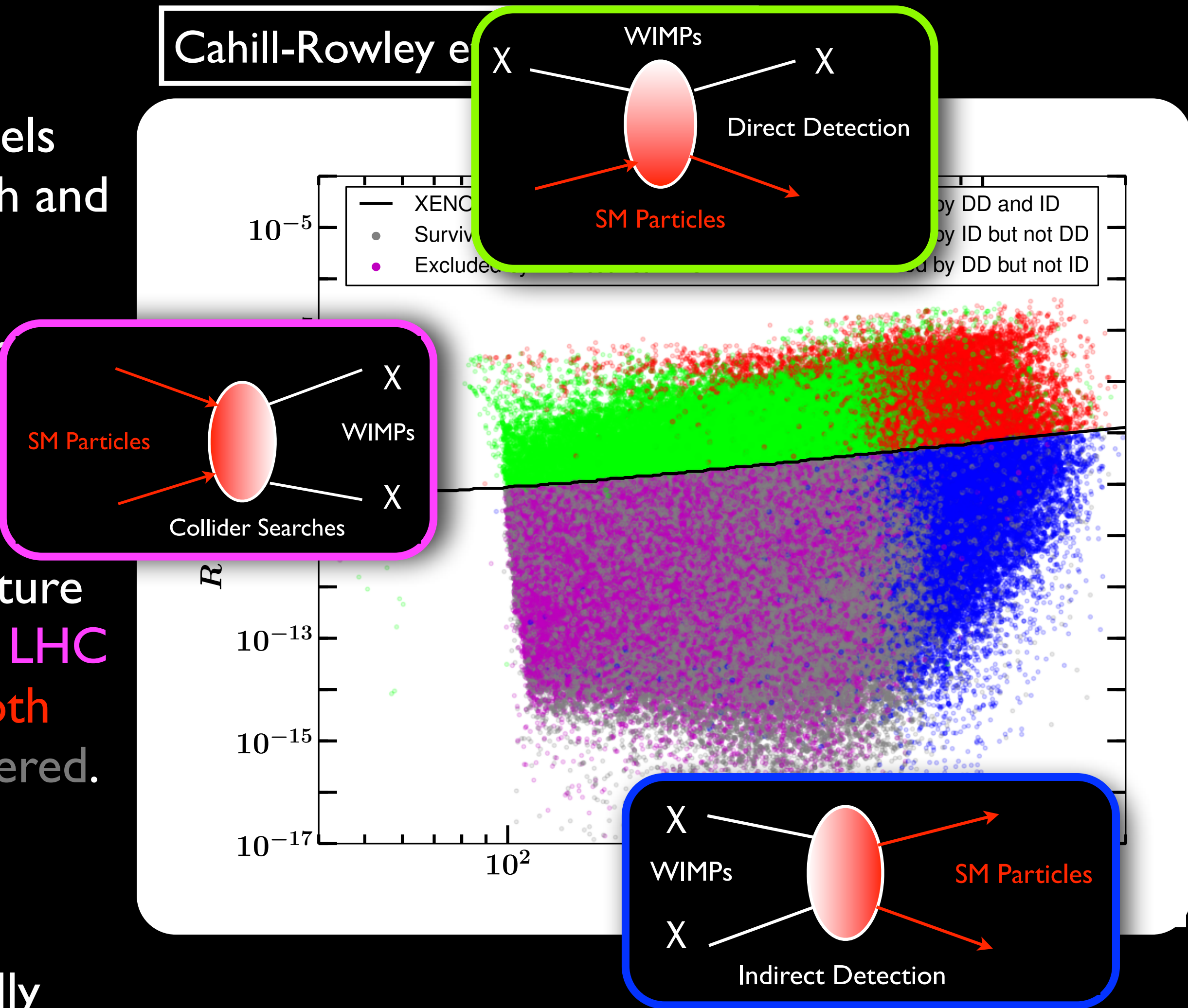
- The MSSM is still our best-studied and best-motivated vision for physics beyond the Standard Model.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM' parameter space in the plane of the WIMP mass versus the SI cross section.
- The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1ton only, CTA only, both Xenon and CTA, or can't be discovered.
- It is clear that just based on which experiments see a signal, and which don't, that there could be (potentially soon) suggestions of favored parameter space(s) from data.

Cahill-Rowley et al, 1305.6921



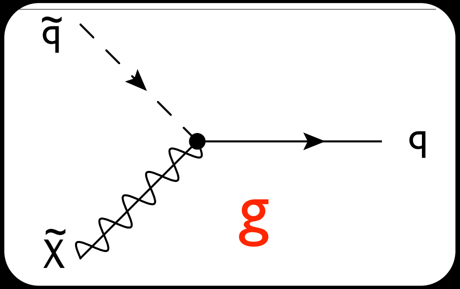
pMSSM

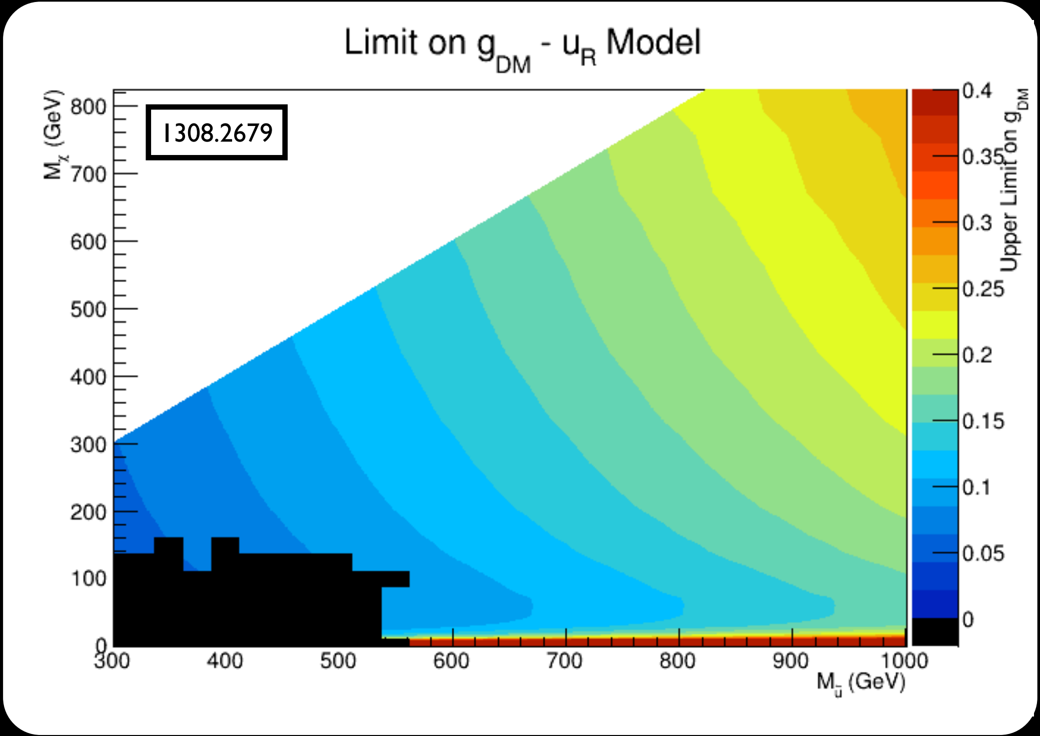
- The MSSM is still our best-studied and best-motivated vision for physics beyond the Standard Model.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSS parameter space in the plane of the WIMP mass versus the SI cross sec
- The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1ton only, CTA only, both Xenon and CTA, or can't be discovered.
- It is clear that just based on which experiments see a signal, and which don't, that there could be (potentially soon) suggestions of favored parameter space(s) from data.



Simplified Models

- We can also analyze dark matter searches in the context of simplified models.
- These contain the dark matter, and some of the particles which allow it to talk to the SM, but are not meant to be complete pictures.
- As a simple example, we can look at a theory where the dark matter is a Dirac fermion which interacts with a quark and a (colored) scalar mediating particle.
- There are three parameters: the DM mass, the mediator mass, and the coupling g.
- These are like the particles of the MSSM, but with subtle differences in their properties and more freedom in their interactions.
- Just like the MSSM was just one example of a complete theory, this is only one example of a "partially complete" one.





Simplified Models

- Moving away from complete theories, we come to simplified models.

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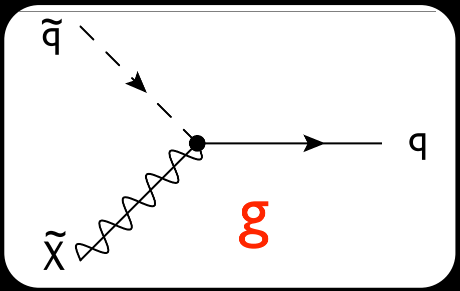
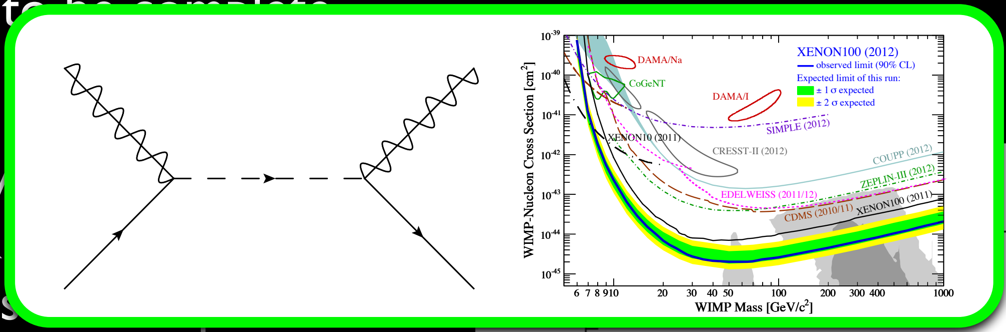
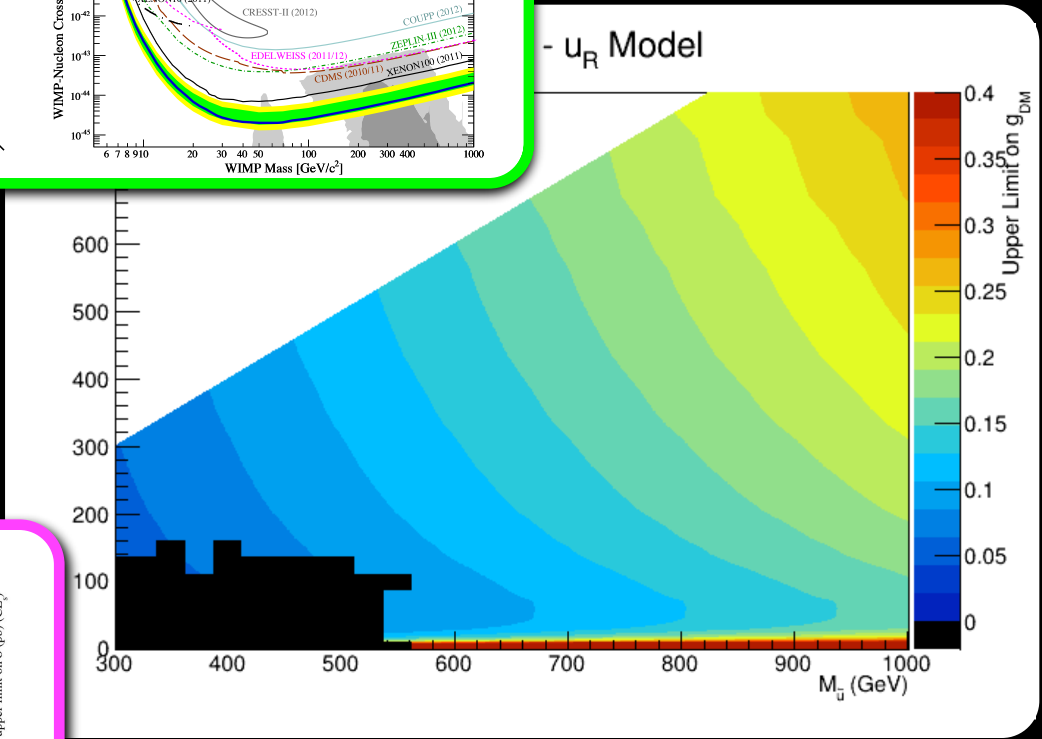
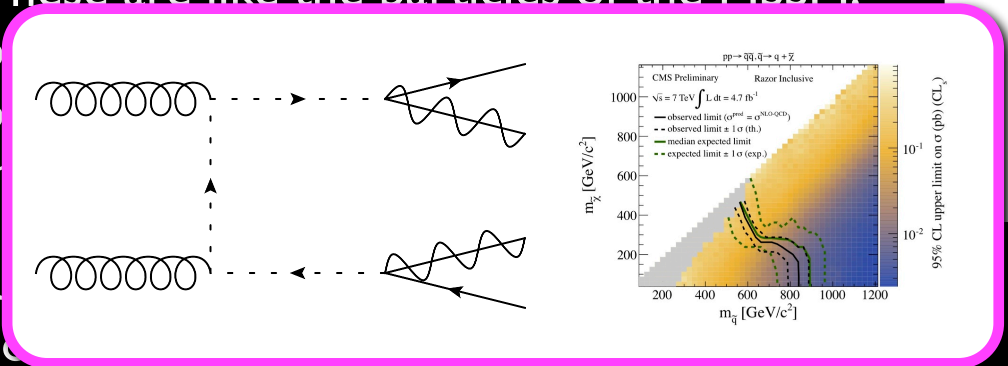


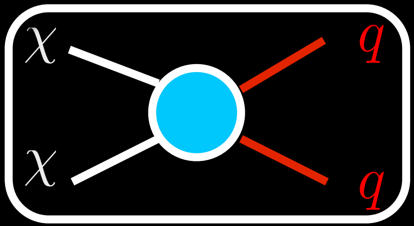




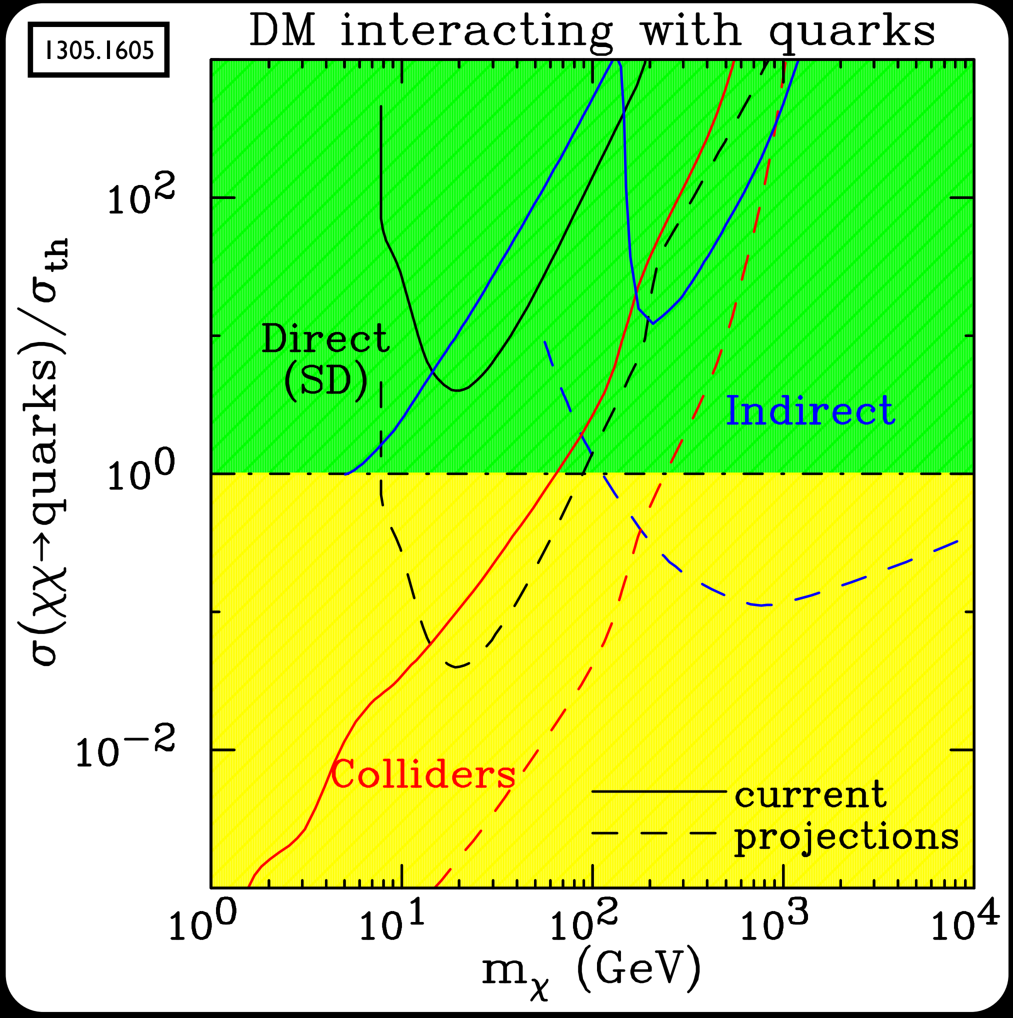


Contact Interactions

- In the limit where the mediating particles are heavy compared to all energies of interest, we are left with a theory containing the SM, the dark matter, and nothing else.
- The residual effects of the mediators are left behind as what look like non-renormalizable interactions between DM and the SM.



- These are the simplest and least complete description of dark matter we can imagine.
- For any particular choice of interaction type, there are two parameters: the DM mass and the strength of that interaction.



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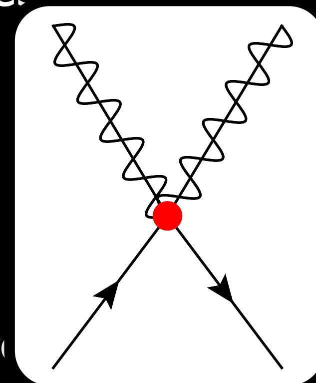

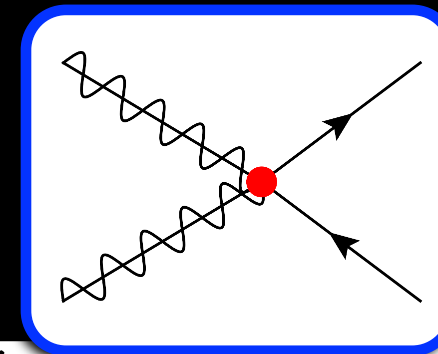

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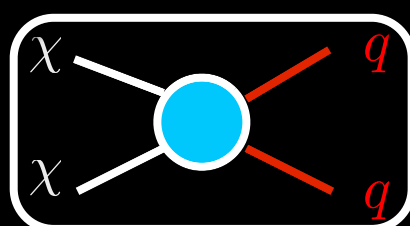

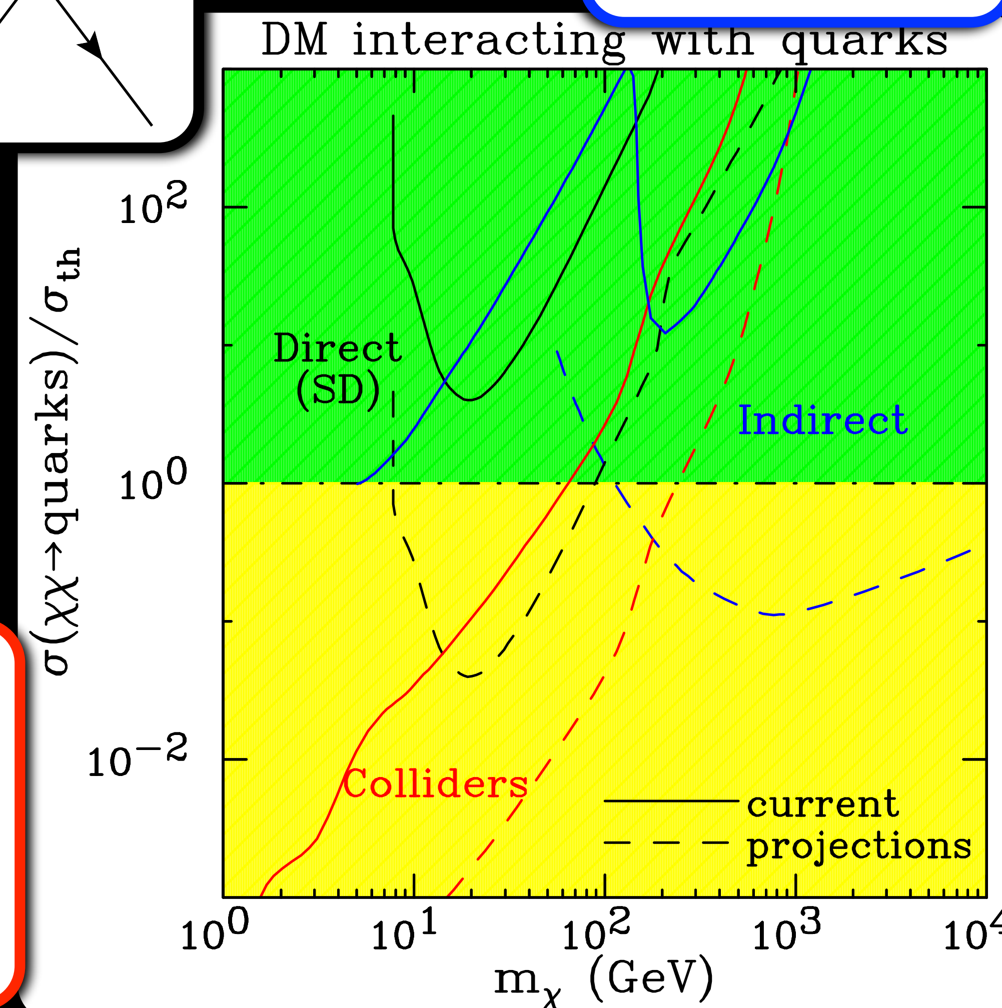

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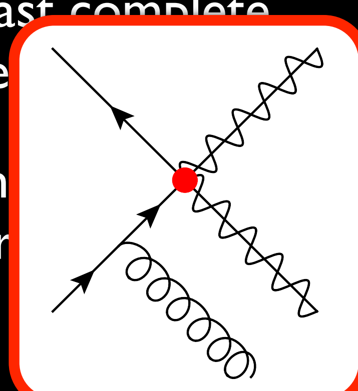

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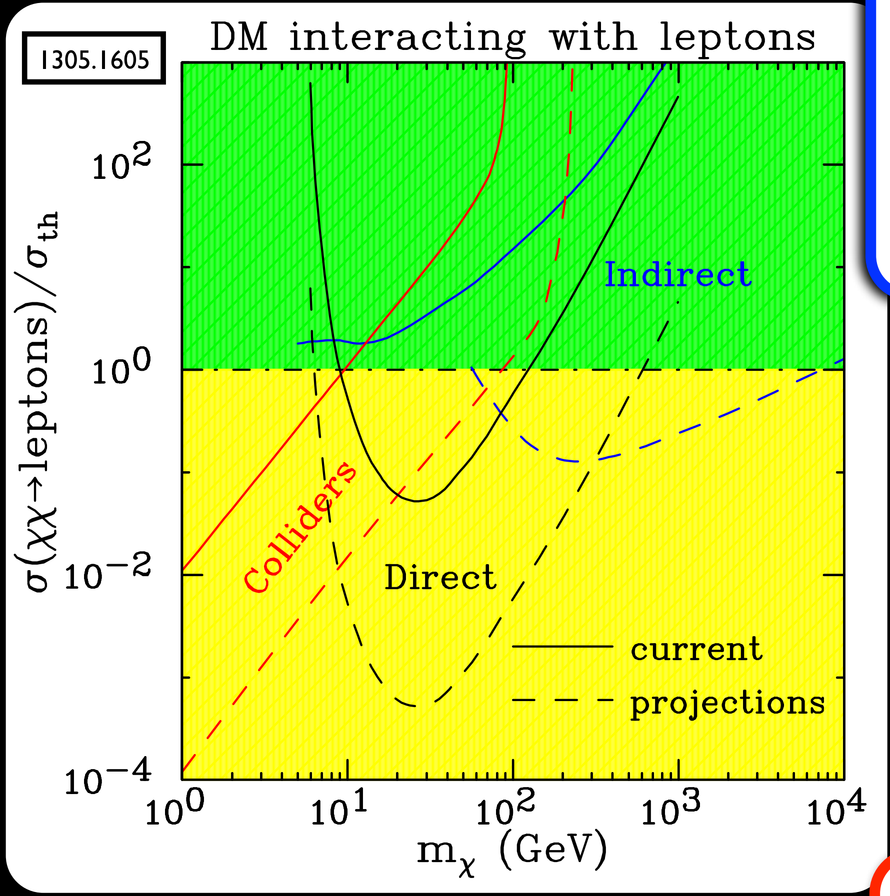
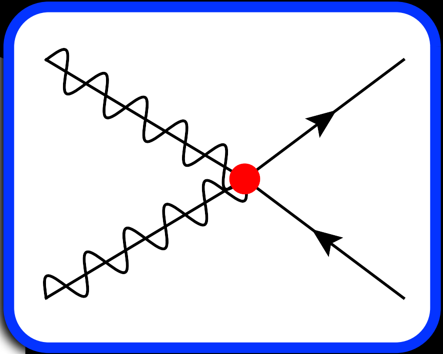
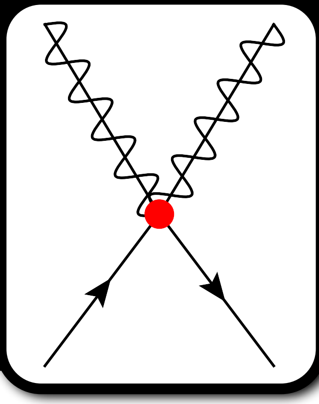
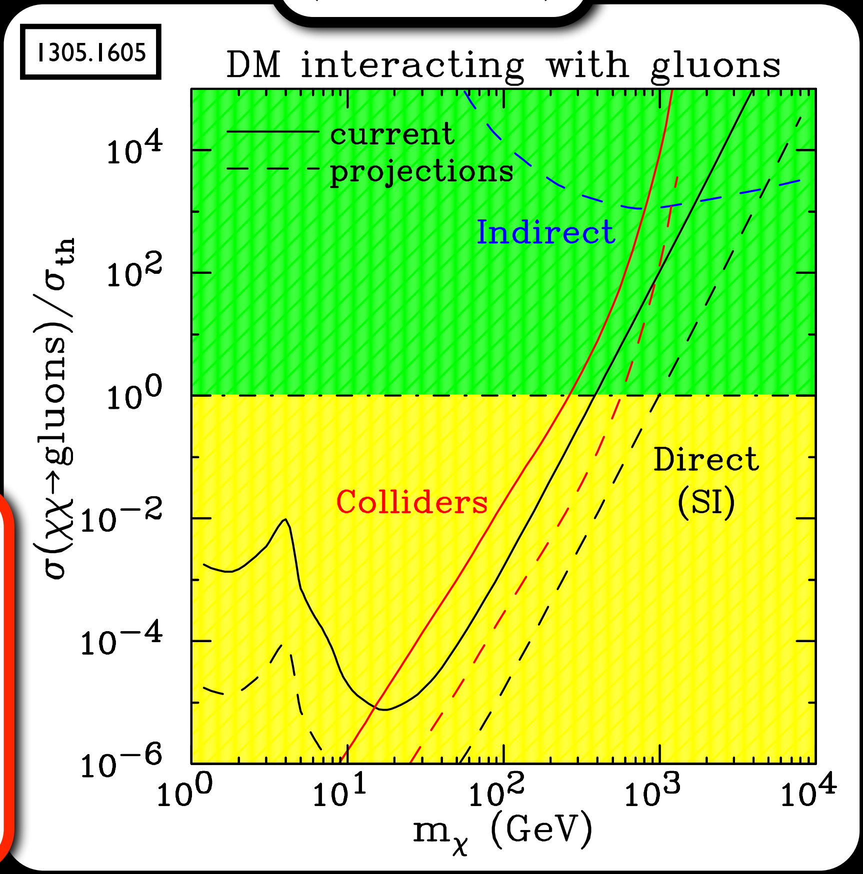
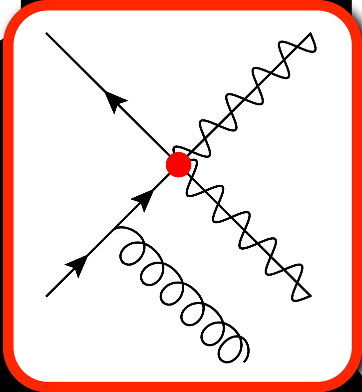
Lepton/Gluon Interactions











A Possible Timeline

2013

2014

2015

2016

2017

2018

- [ ] Mass
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

- 2013


- 2014
- 2015
- 2016
- 2017
- 2018

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

- ☐ ? Mass: < 200 GeV
- ☐ Spin
- ☐ Stable?

Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☑ Quarks / Gluons?
- ☐ Leptons?
- ☐ Thermal Relic?

A Possible Timeline

2013

YOU ARE HERE

2014

2015

2016

2017

2018

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

- [x] Mass: 150 +/- 15 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
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Xenon sees a similar signal.

Two LHC experiments see a significant excess of leptons plus missing energy.

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No jets + MET

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Neutrinos are seen coming from the Sun by IceCube.

- [x] Mass: 150 +/- 15 GeV
- [x] Spin: > 0
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] ✗ Weak Interaction?
- [ ] Higgs?
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Two LHC experiments see a si… lept…

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

☑ Mass: 150 +/- 15 GeV	☑ Mass: 20 μeV
☑ Spin: > 0	☑ Spin: 0
☐ Stable?	☒ Stable?
Couplings:	Couplings:
☑ Gravity	☑ Gravity
☒ Weak Interaction?	☑ Photon Interaction
☐ Higgs?	☐ Higgs?
☑ Quarks / Gluons	☐ Quarks / Gluons?
☑ Leptons	☐ Leptons?
☐ Thermal Relic?	☒ Thermal Relic?

A Possible Timeline

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✓ Mass: 150 +/- 0.1 GeV	✓ Mass: 20 μeV
✓ Spin: > 0	✓ Spin: 0
☐ Stable?	✗ Stable?
Couplings:	Couplings:
✓ Gravity	✓ Gravity
✗ Weak Interaction?	✓ Photon Interaction
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☑ Gravity	☑ Gravity
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The era of dark matter astronomy begins!

Outlook

- Putting together a detailed particle description of dark matter will necessarily involve many experimental measurements.
- Important details such as the mass and spin will hopefully come along as part of that program.
- The US plays a leading role in a vibrant program that covers a huge space of possibility from ultra-weakly interacting particles such as axions and sterile neutrinos to WIMPs and beyond.
- For WIMPs, the three traditional pillars of dark matter searches: direct, indirect, and collider, naturally probe different parts of the space of DM-SM couplings.
  - They are highly complementary to one another in terms of discovery potential.
  - Considered together, they can probe a large fraction of the space of interesting WIMP models in the near future.